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Dry land strength and power training to enhance swimming in-water turn performance

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Dry Land Strength and Power Training to Enhance Swimming In-Water Turn Performance

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USE OF THESIS

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Abstract

Undertaking dry-land strength and power training to increase leg extensor power output is believed to increase a swimmer's ability to start and turn during a swim race. Swimmers generally undertake dry-land strength and power training as part of their overall training regime to increase lower body force output and impulse, in order to improve both swim start and turning performance. Elite swimmers demonstrate faster swimming turn times that are potentially a result of having better strength-power characteristics than sub-elite swimmers. The aim of this research was to quantify differences in dry-land and swimming turn leg extensor force-time characteristics between elite and sub-elite swimmers, and investigate whether short-term ballistic training or maximal strength training is more effective in enhancing leg extensor force-time characteristics during the swim turn in elite and sub-elite swimmers.

To quantify the differences in dry-land and swim turn leg extensor force-time characteristics sub-elite (11 males: 17.4 ± 0.6 y; 10 females: 17.1 ± 0.6 y; mean ± SD) and elite swimmers (15 male: 23.2 ± 2.3 y; 7 female: 21.6 ± 2.5 y) were tested in a cross-sectional design. All swimmers performed a bodyweight and loaded (20 kg females, 30 kg males) squat jump (SJ) on a portable force platform. On the same day, all swimmers completed swimming turn analyses using a force platform fixed within the pool wall. The magnitude of difference between sub-elite and elite groups was estimated using a standardised mean difference (effect size statistic). Elite male and female swimmers had superior swim turn and dry-land force-time characteristics than sub-elite swimmers in all tests. The standardised mean differences between groups ranged from small to very large. The largest differences being unloaded SJ peak velocity (male: 3.07 ± 1.0 $m \cdot s^{-1}$; female: 3.49 ± 2.29 $m \cdot s^{-1}$; standardised mean difference ± 90% confidence limits) and unloaded SJ peak power (male: 2.59 ± 0.79 W; female: 2.80 ± 1.64 W) with elite male and female swimmers demonstrating ~25-50% higher performance than the sub-elites.

To investigate whether short-term ballistic or maximal strength training is more effective at enhancing leg extensor force-time characteristics during the swim turn, twelve elite swimmers (10 males and 2 females 19.4 ± 1.0 y) were assigned to either strength (n=6) or ballistic leg extensor (n=6) training based on their coaching group for a six-week period. All testing was conducted during the final training cycle leading into the 2013 World Championships selection trials. There was only one substantial difference between the strength and ballistic

groups after the six-week intervention. Loaded SJ peak velocity was substantially lower (-0.71 ± 0.42 $m \cdot s^{-1}$; mean ± 90% confidence limits) after six weeks in the strength-trained group. Relative peak power (4.0 ± 2.1 $W \cdot kg^{-1}$), loaded and unloaded SJ peak force (loaded: 195.0 ±122.8 N, unloaded: 155.0 ±152.3 N) and unloaded SJ impulse (2.9 ± 2.1 $N \cdot s$) all showed small but clear improvements with ballistic training over the six-week intervention.

Elite male and female swimmers, exhibit superior leg extensor force time curve characteristics in both dry-land and in pool measures than younger and less experienced swimmers. The greatest differences were in squat jump relative peak power and peak velocity. A 6-week training intervention focused on either strength or ballistic dry-land training yielded small improvements in aspects of the push off stage of the swim turn for elite swimmers. Swimming and strength and conditioning (S&C) coaches should include programming options for both strength and ballistic dry-land training to enhance swim turn performance of their athletes.

Certificate of Authorship of Thesis

Declaration

Except where clearly acknowledged in footnotes, quotations and the bibliography, I certify that I am the sole author of the thesis submitted and titled:

"Using Dry Land Strength and Power Training to Enhance Swimming In-Water Turn Performance"

I certify that this Thesis does not, to the best of my knowledge and belief;

1. Incorporate without acknowledgement any material previously submitted for a degree or diploma in any institution of higher education.
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Signature of Candidate (Julian Jones)

[redacted]

Signature of Principal Supervisor (Prof Robert Newton)

Statement of Contribution by Others

This thesis details original research conducted by the candidate at the Australian Institute of Sport while enrolled in the Faculty of Exercise and Health Sciences at Edith Cowan University.

The thesis includes research articles of which I am the lead author and was primarily responsible for the conception and design of the research, ethical approval to conduct the research, data collection, analysis and interpretation, manuscript preparation, and correspondence with journals.

Where explicitly acknowledged in each experimental chapter, a number of individuals have contributed to the research presented in this thesis.

• Prof. Robert U. Newton (ECU) - Project design, data interpretation, manuscript preparation

• Ass Prof. G, Gregory Haff (ECU) - Project design, data interpretation, manuscript preparation

• Prof. David B. Pyne (AIS) - Data interpretation and manuscript preparation

[redacted]

Signature of Candidate (Julian Jones)

Date: 12 September 2017

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List of Abbreviations

AIS	Australian Institute of Sport
BT	Ballistic trained
EI	Efficiency index
FINA	Federation International De Natation
L	Loaded
OTT	Overall turn time
RFD	Rate of force development
RM	Repetition maximum
RPM	Revolutions per minute
RTT	Round turn time
S&C	Strength & Conditioning
SJ	Squat Jump
SL	Stroke length
SR	Stroke rate
ST	Strength trained
UL	Unloaded

Publications Resulting from the Thesis

Jones J, Pyne D, Haff GG. and Newton RU. A comparison between elite and sub-elite swimmers on dry-land and tumble turn leg extensor force-time characteristics. *Journal of Strength & Conditioning Research.* (In Press) 2017.

Jones J, Pyne D, Haff GG. and Newton RU. Comparison of ballistic and strength training on swimming turn and dry-land leg extensor characteristics in elite swimmers. *International Journal of Sport Science & Coaching.* (In Press) 2017.

Conference Presentations by the Candidate relevant to the Thesis

Jones JV, Planning and Periodisation to Optimise Athletic Performance. ASCA South East Asian Strength and Conditioning Conference, April 22nd, 2017, Singapore, Singapore

Jones JV, Developing the Athlete first for Long Term Success – Planning. Australian Swim Coaches and Teachers Association Conference. April 27th, 2017, Gold Coast, Australia

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Firstly, let me say that this has been quite a journey to get to the point of completing this Thesis. It all started with a conversation with my Supervisor Prof Rob Newton many years ago when he first became a Foundation Professor at Edith Cowan University that led to me beginning this process in the first place. Some ten plus years later it has come to fruition.

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Chapter 1: Introduction

To be successful in competitive swimming, specific training interventions that address all phases of the competitive race are an integral part of the swimmer's overall development plan. Exemplified by Mason and Fowlie (69) swimming performance is traditionally divided into four key phases including the start, free swim, turns, and finish. All swimmers who compete in races that cover distances greater than 50 m, in a long course 50-m pool or short course 25-m pool, will complete each of these critical phases.

The free swim phase has been identified as the largest single independent variable influencing swim performance and ultimately race results (66). While this phase has been the primary focus of inquiry there has also been some examination of the other three phases in a swim race (22, 64, 66, 69). Each phase contributes to the overall race, but these contributions differ in percentage depending on whether the race is in a 50-m (long course) or 25-m (short course). An example is the start phase has been quantified in context of its contribution to the overall race performance of a 50 m race as 30% of the overall race time (53). Depending on the distance of the race being examined this percentage will decrease given the 50 m race is the shortest competitive race (53, 63, 67, 82). In contrast to the start and free swim phase there is little research that examines the impact of the turn phase on overall swimming performance (79). It appears that turn time contributes between ~21-33% of the overall race time in a short course (25 m) pool (16, 59). As the race distance increases the swim turn forms an increasing contribution to the overall race time as it is undertaken more times. Therefore it is considered one of the most influential contributors to the overall swimming race performance (66). There has been little to no specific research undertaken on the finish phase.

When examining the effect of the turn phase on swim performance the majority of research has focused on the style of the turn (16), and kinematics and kinetics of the different turn styles (59). These studies highlight the importance of the maximum force and impulse applied by the swimmer to the wall in reducing total turn time (96). Total turn time is also impacted by other factors such as a reduction in peak drag forces, via the use of a streamlined body position, and effective timing of the peak push off forces during the action of turning (16, 57). Critical evaluation of the relevant studies on swim turn performance indicates that implementing a dry land strength and power training program may transfer to a more powerful and efficient swim turn (58). To date there is a paucity of scientific studies that have directly examined the effects of dry land strength and power training on swim turn time (9). In a study by Haycraft et al. in 2015 she presented synopsis of how many papers were available with the search parameters of Swimming, Dry-land, Strength and Power. These parameters between the years of 1980 and 2013 presented 425 papers. Of the 425 papers found only 6 met the criteria of using leg extensor exercises. A search since 2013 using the same parameters in PubMed has found only a further 3 papers (47).

Swimmers undertake training to enhance all phases of the competitive race with certain elements being addressed depending on what stage of the development pathway the swimmer is at (17). Some training components are sequential in nature and needs the swimmer to attain certain performance parameters before specific types of training will be effective. Whilst many studies have identified a number of characteristics that have an impact on the four phases of the competition race, including turn performance, they have not distinguished if these characteristics are pathway stage or age dependant (12, 13, 52, 58, 64). Knowing which characteristics need to be developed first in sequence helps the swim coach prioritise their training plans year on year. Being able to do this for each phase of the swimming competition race helps both the swim coach and support staff to prioritise both training phases and training content as a swimmer progresses from sub-elite to elite in performance.

Statement of Problem

Many studies on the physical characteristics of swimming have primarily focused on upper body strength characteristics and their effects on swimming performance. Studies undertaken on the lower body have investigated the lower body effect on a swimmers kicking, the start phase and the turn phase. Whilst a number of studies have stated that leg extensor force characteristics are important to swim turn performance, to date there has been no specific research investigating which leg extensor force-time characteristics are important for elite swimmers during tumble turn time performance. Therefore, it is prudent to identify which leg extensor characteristics exert a greater impact on performance and target these characteristics within the training program of the swimmer. Both the swim coach and the strength and conditioning (S&C) coach program are seeking a performance gain in all the leg extensor force-time characteristics. Enabling the swimmer to achieve optimal capacities in the identified leg extensor characteristics at an earlier age can then shift the priorities of training program to other components of the competitive swimming race.

The S&C coach and the Swim Coach have two main components of the yearly plan, the off-season and the competition season, in which they can prioritise key performance characteristics. The leg extensor force-time curve characteristics are likely to improve if prioritised during the off-season and then maintained over the competition season. Given that the S&C coach cannot expect to make gains all year round, knowing which of the leg extensor force-time characteristics to prioritise permits sequential development of program training loads over multiple years.

Aims

The aims of the experimental studies contained in this thesis were to identify which leg extensor characteristics were substantially different in elite swimmers from sub-elite, and investigate whether increases in strength and power in the characteristics identified positively influence swimming tumble turn performance. The central research question and specific aims of each experimental study are as follows:

Central Research Question: What are the differences in dry land and swimming turn leg extensor force-time characteristics between elite and sub-elite swimmers, and does an increase in dry land strength or ballistic training result in a significant improvement in total turn time performance?

Central Hypothesis: Swimmers who generate higher leg extensor force and velocity during dry-land and in-pool tumble turn measures will have faster turn times and race performances.

Specific Aim 1: To determine which dry-land measures of strength and power differentiate between two levels of swim turn ability.

> Hypothesis: Elite swimmers express higher peak force, average force and relative power at higher velocities during swim turns as well as during dry-land squat jump testing when compared to sub-elite swimmers.

Specific Aim 2: Establish the effects of two different short-term dry-land interventions with elite level swimmers on their leg extensor force-time characteristics and subsequent overall tumble turn performance.

Hypothesis: The implementation of a ballistic dry-land training intervention will yield significant improvement in the dry-land and in-pool leg extensor force-time characteristics of elite swimmers and decrease total turn time.

Significance of thesis

Kinematic and kinetic analysis of the swimming turn has not been rigorously investigated compared with the other phases within competitive swimming. Therefore, the thesis will quantify the impact of resistance training on this key phase of the swimming race. While some studies have examined the contribution and effect of the turn in relation to the overall competition race performance, to the author's knowledge no studies have examined the direct effect that dry-land strength and power training may have in decreasing overall race turn time.

In international swimming, athletes dedicate many hours of training to attain small increments of improvement or marginal gains in their overall performance. To stay in contention for an Olympic medal, a swimmer must improve his or her performance ∼1% within a competition (heats to finals) and by ∼1% within the year leading up to the Olympics (85). Even during the taper period, a competitive swimmer can only expect to change their overall swimming performance by ~2.2% (76). This taper period is seen as crucial to the overall competitive performance of a swimmer. Therefore, if a high-level swimmer can decrease their overall race time by >1% over a twelve month period, this could make them significantly more competitive in international level races.

Synopsis of thesis

This thesis contains six chapters. Each experimental chapter of the thesis (chapters three and four) is presented in manuscript format according to the requirements of the scientific journal to which it was submitted, with corresponding Abstract, Introduction, Methods, Results and Discussion sections. Consequently, there is some repetition between the chapters contained within this thesis. All references are located at the end of the thesis to improve the flow of the document.

Chapter One – Introduction.

This chapter provides background on the phases of competitive pool swimming and the relevance of the research being undertaken within this Thesis.

Chapter Two – Review of Literature

This chapter examines the major physical and performance related topics in swimming performance. This review includes performance components of competitive swimming, kinetics and kinematics of the swimming turn, physiological demands of the swimming training, application of strength and power characteristics in swimming turn performance and optimising improvements in swim turn performance while conducting concurrent training.

Chapter Three – A comparison between elite and sub-elite swimmers on dry-land and tumble turn leg extensor force-time characteristics profiles what are the differences between elite and sub-elite swimmers in relation to pool turn and dry-land leg extensor characteristics.

This chapter contains the content of the paper accepted by the *Journal of Strength and Conditioning Research,* May 2017

Chapter Four – Comparison of ballistic and strength training on swimming turn and dry-land leg extensor characteristics in elite swimmers examines the effects of a 6-week intervention of two dry-land training modalities on swim tumble turn performance.

This chapter contains the content of the paper accepted by the *International Journal of Sports Science and Coaching, July 2017*

Chapter Five – Discussion

This chapter examines the impact the outcomes of the experimental work and their importance in the progression of knowledge pertaining to identifying and training the pertinent leg extensor characteristics.

Chapter Six – Research Outcomes

This chapter presents the primary findings of the thesis, practical outcomes and application of new knowledge, limitations of the research and suggestions for further research in the field.

Chapter 2: Literature Review

Introduction

International swimming is a highly competitive sport with many nations now fielding teams. Swimmers compete in four recognised strokes across distances of 50 m to 1500 m in both a long course 50-m and short course 25-m pool. The highest levels of competition include a long course and short course Word Championship every two years and a long course Olympic Games every four years. As the level of competition in swimming has increased, so has the research into quantifying the components of competitive races and how to optimise the swimmers performance. Typically, these investigations have categorised the competition performance into four key phases; the start, free swimming, turns and finish (69).

In competitive swimming, along with increased participation, the number of nations fielding teams at the highest levels of competition has increased. This has resulted in an increased specialisation in both stroke and distances swum, as well as a greater interest in improving each of the four key phases of the competition performance. This review focuses on the following topics relating to performance in competitive swimming:

- Performance components of competitive swimming
- Phases and the components of the swimming turn
- Application of strength and power characteristics in swimming and swimming turn performance
- Optimising improvements in swim turn performance whilst conducting concurrent training

The level of competitive performance in swimming has steadily increased as the sport has progressed from an amateur toward a professional sport. Early research examining swimming performance centred on what was deemed the critical phase of the competitive race, the free-swimming phase (27, 45, 51). To date there has been limited research examining the leg extensor force-time curve characteristics during turn performance, the effect of dry-land resistance-training methods on turning performance characteristics, implications of optimising force generating capacities during turn performance, and the impact on overall race performance.

Performance components of competitive swimming

Competitive swimming performance is determined by physiological, psychological and anatomical factors, with traditional swim training mainly focused on improving the swimmer's physiological capacities (7). These physiological capacities can be and are developed primarily by in-pool training and supported by dry-land training activities which are constructed by the coach when developing the overall training plan.

All swimmers who compete in races that cover distances greater than 50 m, in a long course 50-m pool or short course 25-m pool, will complete each of the four critical phases contained in a competitive swimming performance; starts, free swimming, turns and finish (46, 69, 91). A majority of the swimmer's time is spent within the free-swimming phase of the race, especially as the race distance increases and when performed in a 50-m pool.

Given that within a race the swimmer spends the greatest amount of time in free swimming, the majority of the swimming research has examined the free swimming phase as it is the largest single independent variable influencing overall swim performance and ultimately race results (66). Free-swimming has been characterised as the product of stroke length (SL) and stroke rate (SR), which combine to determine swimming race velocity (15, 25). Early studies overestimated the contribution of the SL as the equation used did not take into account the start, turn and finish phases being different to the free swimming phase (27, 28). Subsequently an efficiency index (EI) was developed for the coach and swimmer in which video analysis was used to determine the time (seconds) needed to complete 1 or 2 stroke cycles. The EI places emphasis on the swimmer having a longer SL and a lower SR as being more efficient. To establish SR, SL, SV and EI the following formula are used (4):

$$\textit{Stroke Length (m)} = \textit{meters covered per swim stroke}$$

$$\textit{Stroke Rate } (n \cdot sec^{-1}) = \textit{number of strokes per second}$$

$$\textit{Swim Velocity} = \textit{Stroke Length x Stroke Rate}$$

$$\textit{Efficiency Index} = \textit{Swim Velocity x Stroke Length}$$

Ultimately, a higher EI would be representative of a higher performance level when comparing swim performances (91). The practise of determining the EI is now commonly known as a competition race analysis (63, 65, 66, 68, 69), a practice that has been a key swim performance diagnostic since 1989 (2).

While the primary focus of much of the scientific inquiry into swimming has focused on the free-swimming phase, it is important to note that the other three phases contained in a swim race also exert an impact on overall swim performance (22, 64, 66, 69). Starts can be performed in various ways, but the two most common types are grab and track (10). These two start variations are dominated by the leg extensors in providing the forces necessary to effectively initiate a race. The start phase performance is a combination of reaction time, vertical and horizontal force off the block and a low resistance during underwater gliding (101). The start phase can contribute up to 30% of the overall race time and has a major impact on the race outcome (10). As the phase contains both horizontal and vertical force application it appears these qualities are trainable - support for this assertion is provided by a moderate correlation between vertical jumping performance ability and swim start performance variables of flight and glide times (r=-0.68) (103).

In contrast to the start and free-swim phase there is very little research that examines the impact of the turn phase on overall swimming performance (13, 16, 79). The available literature indicates that turn time contributes between ~21-33% of the overall race time in a short course (25-m) pool (16, 59). As the swim race distance increases the swim turn increases its contribution to the swim performance and may be one of the most influential contributors to overall swim performance (66).

The final phase outlined in the research is the finish (69). Few scientific studies have examined this phase of the race as it is often considered part of the free swim phase, and effects of SR and SL are the main aspects to discern from this phase (69). This phase incorporates the period of time when the swimmers head passes the 5 m distance from the finish wall until the hand touch.

Phases and the components of the swimming turn

The swim turn is usually divided into five distinct phases that include: 1) Inward-Turn, 2) Rotation, 3) Push Off, 4) Underwater and 5) Outward-turn phases (63). All of the phases together are referred to as Round Turn Time (RTT) in a majority of studies (13, 16, 31, 59). Generally, RTT can be quantified from any pre-determined starting marker point within the pool and this contributes to the inconsistent definition of the RTT in the scientific literature (13, 16, 96). Regardless of the method used to calculate the RTT it is clear that the process of turning has a significant contribution to overall swim performance. As noted previously, the contribution of the turn to the overall swim performance increases during longer events because more turns are performed in these races (16).

When examining the first of the four phases of the swim turn, the inward-turn, the beginning of this phase is when the swimmer's approach is 7.5-m from the wall of the pool. This marker has been traditionally set in a number of competition analysis studies (63, 65). Commencement of the rotation phase will begin within this distance and is judged by the swimmer depending on external cues, as well as anatomical and physical characteristics. The initiation of the phase is also dependent upon which type of turn they use as to how close to the wall this initial rotation occurs (62).

The second phase of the swim turn, or the rotation, occurs when the swimmer's body is rotated, by either performing a tuck or a tumble to allow the athlete's feet to make contact with the wall and transition into the push-off phase (14, 61). This phase is characterised differently depending upon the style of turn performed. For example, during a tumble turn, the rotation phase is defined from the point when the swimmer's head is submerged at initiation of the tumbling motion until wall contact is made. For a touch turn this phase is characterised from when the swimmer's hands touch the wall to when the feet of the swimmer make contact with the pool wall (59). Generally, regardless of the turn style commencement of the rotation phase is undertaken within a 5-m distance from the pool wall.

The third phase of the swim turn, referred to as the push off, is the portion of the turn in which the leg extensors apply force to the wall of the pool to initiate the swimmer's changing direction. This phase includes the swimmers overall contact time on the wall and the resultant velocity attained by the swimmer after contact is completed (57). A number of studies have examined the variables associated with force application during this phase and indicate that the maximum normalised peak force applied to the wall, followed by the total impulse has the greatest contribution to the overall turn time (13, 59, 79, 99). Normalised peak force and impulse were also different between different levels of swimmers with elite level swimmers expressing a higher average impulse and peak force than sub-elite or recreational swimmers (59). Thus the contribution of this phase to the overall RTT not only depends on the force generated, but also on the length of time of the swimmer applies force to the wall, and the rate of that force application (i.e. rate of force development) (3).

The fourth phase, or underwater phase, refers to passive gliding of the swimmer underwater after the leg extensors have applied maximal force, the feet have left the wall, and the swimmer is propelled under water (57, 59). The holding of a rigid outstretched body, or streamlined position is also essential during this phase to optimise the overall RTT and thus overall race time. Any movement by the body from a rigid streamline position in the underwater position will increase hydrodynamic drag and reduce velocity, thus increasing the overall RTT (57).

The final phase, or the outward-turn, is the active section that covers the distance left from completion of the underwater phase back to the initial inward-turn mark, in this case 7.5 m as per competition analysis studies (69). Under Federation Internationale De Natation (FINA) rules (35) a swimmer may stay underwater until the 15 m mark, thus the outward turn phase will make up only half of the underwater component a swimmer may utilise. The distance a swimmer stays underwater is determined by how well a swimmer can perform, and how well-developed their turning and streamline skills are. Most swimmers do not utilise the full distance of 15m available to them due to capability factors.

While all turns contain similarities in their basic turning phases the exact type of turn used in competitive swimming is dependent upon the FINA-mandated stroke for the event contested by the swimmer. For example, the breaststroke and butterfly stroke utilise a touch turn technique, while the freestyle and backstroke use the tumble turn technique (35). Even though these swim strokes are markedly different during the second phase of turning, they are virtually identical during the push off phase (96) and therefore can be utilised in the analysis of forces related to turning time. Specifically, the force-time characteristics of these different turning techniques can be examined collectively to quantify the contribution of the push off phase to overall turning time and swimming performance.

The two types of turns undertaken in competitive swimming are performed in the following manner; the swimmer executes a tumble turn without touching the wall with the hands, starts the movement of the body around a nearly horizontal transverse axis. This sequence is followed by a twisting rotation around the longitudinal axis of the body before, during and after push off phase (79). The swimmer executes a touch turn in which the turn starts with touching the wall with both hands, rotation around the longitudinal axis of the body during the touch, followed by rotations around the transverse and frontal axes until a lateral body position for the push off phase is attained. During and after push off, rotation is continued until the body is in the prone position in both types of turn (79).

Application of strength and power characteristics in swimming and swimming turn performance

The quantity, quality and frequency of exercise performed during training largely determine the degree of adaptation (25). Given the predominance of a swimmer's training is pool-based, some 3 to 4 hours per day (23, 24), the ability to provide appropriate training time to modalities that enhance leg extensor force-time curve characteristics is limited by both the weekly and yearly schedule, as well as the competing training priorities.

To achieve a high peak force during swim turns, swimmers must train with resistances high enough to engage higher threshold motor units associated with the type II muscle fibres (72). Since this type of loading is low in training volume in most swimming programs the implementation of dry-land strength and power training becomes important to increase the athlete's force generating capacity during turning (57). Therefore, implementation of a strength and power based training program which targets development of the leg extensors should increase both peak force and rate of force development during turning. Based upon this line of reasoning, swimmers have been strongly encouraged to incorporate lower body dry-land strength and power training as part of the overall development process (12). While training the leg extensors has been recommended for swimmers, there is limited data examining which resistance training methods most effectively translate into improved swimming performance. There are a multitude of different training variables and exercises including squats, leg press, single leg squats, power cleans, clean pulls and deadlifts which can be used to enhance leg extensor strength and power capacity (19). To optimise which modalities are applicable to the turning movement and determine which methods have the greatest potential to transfer training effects in to swim turn performance, examination of the movement patterns involved and the planes in which these movements occur during the performance of both swim turn styles must be undertaken (33, 44). Additionally, selection of the applicable training modality is dependent on the type of training being targeted and the physiological characteristics of the athlete being trained (30).

To increase leg extensor force and power the swimmer must undertake a specifically designed resistance training program that targets these qualities. Various training modalities designed to increase the force and power output of the leg extensor have been investigated in a variety of sports including cycling, running, basketball and football (32, 34, 92, 93). However, there are few investigations into the use of these types of training methods with swimmers and the direct transfer of dry-land training effects to the push phase of the swim turn. Several studies have identified that leg extensor force production to be a factor in turn performance

(59, 96) as such dry land strength and power training programs may enhance the swimmer's ability to decrease their overall RTT, which may lead to a reduction in overall event time. Takahashi et al. (96) reported that the knee joint was at approximately 120° of flexion when peak force was observed during the push off phase of a swim turn, which is similar to the knee angle (120°-140°) at which peak force occurs during a vertical jump (96). Additionally, forces generated at these knee angles also relate to other performances such as those seen in sprinting and weightlifting (42, 94). The type of training modality chosen for development of force generating characteristics needs to be complemented with correct movement technique to effectively induce a transfer of training effect from a power output and movement efficiency perspective.

In support of the contention that the force application profile during the turn push off phase is important, swimmers who exhibit faster RTT times demonstrate significantly higher peak forces (12), reduced wall contact time (16, 96) and greater mean impulse (96) than slower swimmers. Additionally, Lyttle et al. (59) reported that the ability to generate higher propulsive forces during the turn push off phase results in a higher final velocity for the swimmer off the wall. A reduction in RTT is highly correlated ($r=0.90$, $p<0.05$) with 50 m swim times (13). Thus, if a swimmer can decrease their overall RTT time they can reduce their race time and improve their overall swimming performance, increasing their chances for competitive success.

Optimising improvements in swim performance whilst conducting concurrent training – pertaining to swim tumble turns

In many sports, it is accepted by the coach and support staff that to maximise physiological adaptations and avoid overtraining, proper management of training program variables including the intensity, frequency and volume of training is required. This is especially important in sports where both endurance and strength need to be enhanced simultaneously to optimise performance (36). Swimming training is invariably made up of both dry-land strength/power training and in water aerobic/anaerobic training from an early age in competitive swimmers. Training each of these modalities results in specific physiological adaptations directly associated with the training modality (41).

Aerobic training can improve VO_{2max} by increasing the number and density of mitochondria, aerobic specific enzymes, intramuscular glycogen stores and increased capillary density of the muscle (54). Aerobic training leads to a modest increase in the size of type I muscle fibres as they have a larger number and density of mitochondria. As a result of aerobic training, type II muscle fibre mass may not increase and the actual size of the muscle fibre can decrease (50). This is thought to occur as a result of what is known as the interference effect and the subsequent molecular inhibitions that aerobic training elicits (43).

Strength training has the effect of stimulating muscle hypertrophy via an increase in the number of myofibril proteins. Muscle hypertrophy usually occurs in both type I and type II muscle fibres and their associated neural activations via motor unit recruitment patterns (43). In strength training the mass density of mitochondria in the muscle fibre decreases in contrast to the increase in muscle mass (43). This is the case when strength training is done in isolation, but when conducted concurrently with aerobic training some or all of these strength and power adaptations can be muted (1).

Each of the modalities of endurance and strength training elicit distinct and often divergent adaptive mechanisms (86, 87). This has led to much debate and uncertainty in how to apply the various types of training either separately or concurrently to gain the optimal performance outcome by coaches and scientists (55). The reality of many sports is the coach must implement a concurrent training regime to enable the athlete to enhance all of the capacities needed to gain a performance improvement. The key is to be able to periodise and plan the training year to account for the different training and interference responses (77).

Chronic and acute interference effects have been proposed to explain strength inhibition during concurrent training (55). One theory related to chronic interference effects suggests that the adaptive mechanisms of skeletal muscle cannot contend with both strength and endurance training simultaneously. Acute interference effects may be related to residual fatigue from the endurance component of concurrent training and as such compromises the muscle fibre’s ability to develop tension during the strength element of concurrent training (29).

In swim training combining strength and aerobic training is common practise, although minimal investigations have been undertaken to examine the interference effect as a result of these training practices (6). In other sports such as cross country skiing, rowing and cycling, studies have demonstrated positive effects for concurrent training modalities within the training week when training volume and intensity are accounted for (1). Research across different sports indicates that training either strength or endurance on separate days leads to a greater increase of strength than when undertaken on the same day (86). Additionally, when the athlete has to undertake multiple training sessions in one day the sequencing and recovery periods between each training modality needs to be considered to optimise the effect from each training session. Baar (8) recommends a minimum of three hours of recovery between each training session be programmed to allow for molecular levels to return to baseline. This period would limit inhibition of cellular activity induced by either strength or endurance training modalities.

In rowers a greater enhancement of strength and muscle power was evident when strength training involved a moderate number of repetitions and not performed to failure while in concurrent training (49). This outcome alludes to the question of having to manipulate the volume and intensity of the training week to facilitate optimal gains. Wilson et al. (102) asserts that the interference effect on strength training is a factor of the modality, frequency and duration of endurance training. Athletes should avoid long low intensity endurance exercise in preference to high intensity as it can result in lower decrements in hypertrophy, strength and power.

Strength training can lead to an enhanced long term (>30 min) and short term (<15 min) endurance training capacity in both well- and highly-trained endurance athletes (1). This adaptation is highly evident when high volume, heavy resistance training protocols are applied. For example, cross-country skiers can increase their ballistic strength capacities with no effect on their aerobic capacity while undertaking a concurrent training regime that has a decrease in their aerobic training of 20%. An increase in explosive strength capacity enabled the cross-country skiers to be more economical in their sport performance from an increase in their sport-specific endurance work economy (71). Consideration of this outcome should be factored into planning and programming for specific priority training phases of the concurrent training year.

To optimise the strength gains in sprint swimming, Haycraft et al. (47) recommends the overall swimming load should be reduced to no more than 5000 m per day to minimise the effects of neuromuscular fatigue. The concept of minimising neuromuscular fatigue is also identified by the fact that power is the variable most affected by concurrent training (102). To help minimise this fatigue, endurance sessions need to be scheduled to optimise the effect of the following or preceding strength session. As a guide, high intensity endurance sessions should be undertaken early in the day. These sessions can be followed after fully refuelling the athlete and after a minimum of three hours recovery prior to the strength training session. To improve the endurance response to a low intensity endurance session, consider performing the strength training session immediately after the low intensity, non-depleting endurance session as the strength training session results in a greater stimulus for the endurance adaptation than just an isolated low intensity endurance training session (8).

Summary and Implications from Literature Review

Competitive pool swimming presents a complex training environment where all four identified phases of the race are addressed to enhance the swimmer's ability to enhance performance. The demands of the strength and power dry-land training concurrently with the aerobic and anaerobic in pool training must be considered in the context of optimising the physical requirements within the four identified phases of the competitive pool race. To date there has been limited research into the leg extensor force-time curve characteristics used in the turn phase of pool racing. Gaining an understanding of which leg extensor force-time curve characteristics have a greater performance effect on the overall speed of the turn phase and how they can be improved, becomes increasingly important when only small performance shifts in elite swimmers across a competition year are attainable.

Understanding the phases of the completive pool swimming race and the expected performance shifts across the competitive year, enables both the swim and S&C coach to identify which of the phases to prioritise and when within the training plan. Identifying what leg extensor force-time curve characteristics within the turn phase are performed at higher levels by elite level swimmers then allows the coaching staff to train these characteristics at either an earlier age, or with a higher priority within the training plan. There are few studies that have examined the leg extensor force-time curve characteristics used during the turn phase, and no studies that examine which training modality within a concurrent training environment has a greater performance enhancement on these characteristics. This knowledge can then be used in the planning and prescription of training in a prioritised approach to enhance the primary leg extensor force-curve characteristics, turn performance, and ultimately overall race performance

Declaration for Thesis Chapter 3: A comparison between elite and sub-elite swimmers on dry-land and tumble turn leg extensor force-time characteristics

Declaration by candidate

In the case of Chapter 3 the nature and extent of my contribution to the work was the following:

Nature of contribution	Extent of Contribution (%)
Julian V. Jones	70%

The following co-authors contributed to the work:

Name	Nature of Contribution	Extent of contribution (%)
Robert U. Newton	Manuscript review	10%
G. Gregory Haff	Data interpretation and manuscript review	10%
David B. Pyne	Data interpretation and manuscript review	10%

Candidate's Signature: Date: 11 June 2017

Declaration by co-authors

The undersigned hereby certify that:

1. The above declaration correctly reflects the nature and extent of the candidate's contribution to this work, and the nature of the contribution of each of the co-authors.
2. they meet the criteria for authorship in that they have participated in the conception, execution, or interpretation, of at least that part of the publication in their field of expertise;
3. they take public responsibility for their part of the publication, except for the responsible author who accepts overall responsibility for the publication;
4. there are no other authors of the publication;
5. potential conflicts of interest have been disclosed to (a) grant bodies, (b) the editor or publisher of journals or other publications, and (c) the head of the responsible academic unit; and
6. the original data are stored at the following location(s) and will be for at least five years from the data indicated below;

Location(s): Australian Institute of Sport – Strength & Conditioning Department

(Please note that the location(s) must be institutional in nature, and should be indicated here as a department, centre or institute, with specific identification where relevant)

Signature 1 Date: 9 June 2017

Signature 2 Date: 9 June 2017

Signature 3 David Pyne Date: 9 June 2017

Chapter 3: A comparison between elite and sub-elite swimmers on dry-land and tumble turn leg extensor force-time characteristics

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Abstract

Elite swimmers demonstrate faster swimming turn times that are potentially a result of having better strength-power characteristics than sub-elite swimmers. We quantified differences between dry-land and swimming turn force-time characteristics in elite swimmers and sub-elite swimmers. Sub-elite (11 males: 17.4 ± 0.6 y; 10 females: 17.1 ± 0.6 y) and elite swimmers (15 male: 23.2 ± 2.3 y; 7 female: 21.6 ± 2.5 y) were tested in a cross-sectional design. All swimmers performed a bodyweight and loaded (20 kg females, 30 kg males) squat jump (SJ) performed on a portable force platform. On the same day, all swimmers completed swimming turn analyses using a force platform fixed within the pool wall. The magnitude of difference between groups was estimated using a standardized mean difference (effect size statistic). Elite male and female swimmers had superior swimming turn and dry-land force-time characteristics to sub-elite swimmers in all tests. The standardized mean differences between groups ranged from small to very large. The largest differences were SJ peak velocity unloaded (3.07 ± 1.0 m/s males, 3.49 ± 2.29 m/s females; standardized mean difference ± 90% confidence limits) and SJ peak power unloaded (2.59 ± 0.79 w male, 2.80 ± 1.64 w female) with elite male and female swimmers ~25-50% higher performance than the sub-elites in both characteristics. Elite swimmers exhibit superior strength and power characteristics for the swimming turn compared with younger and less experienced swimmers. A well-planned and executed strength and conditioning program is needed for emerging swimmers to develop these qualities as they transition to senior levels.

Key Words: force, velocity, power, swimming turn, performance

Introduction

In competitive pool swimming, overall performance is optimized by the three major components of the race: the start, free swimming and the turn (98). In relation to the turn, identifying which characteristics that elite swimmers perform better than sub-elite swimmers would provide valuable information for improving pool and dry-land training programs.

The ability of the swimmer to effectively time the peak push-off forces during a turn is highly correlated with the turning speed (16, 60). Critical evaluation of swim turn performance indicates that strategies designed to improve the effectiveness and magnitude of forces applied during the process of turning may result in a faster turn (96). Implementation of an effective dry-land strength and power training program is needed to develop neuromuscular qualities that can be directly transferred to a more powerful and efficient swim turn (58). The leg extensor muscle groups contribute predominantly to the swim turn from when the swimmer's foot makes contact with the wall until sufficient impulse is applied to propel the swimmer away from the wall.

Generally, research on the turn phase in swimming has focused on technique specifically the kinematics and kinetics of the different turn styles (16, 59). Almost all of these studies indicate that applying higher force and impulse during execution of a turn reduces the total turn time (72). Only one study has directly examined the influence of leg extensor force-time characteristics on swim turn time (9). Several studies have examined the effect of dry-land strength training on swimming performance (5, 37). While these studies provided useful information, they failed to examine the push off stage of the turn and therefore have limited application to the development of dry-land training programs that target specific force-time curve attributes associated with effective swim turn performance.

The swim turn is usually divided into five distinct stages that include: 1) inward-turn, 2) rotation, 3) push off, 4) underwater and 5) outward-turn (63). All of these phases are referred to as the overall turn time in the majority of published studies (11, 13, 59, 96). The turn time can be quantified from any pre-determined starting marker point within the pool, although methodological differences between studies has contributed to an inconsistent definition (12, 16, 96). Regardless of the method used to calculate the turn time it is clear that the process of turning contributes substantially to the overall swim performance, especially during longer events as a function of the number of turns performed in these races (16).

One commonly used turning method is the tumble turn (79). The tumble turn is undertaken during competitive freestyle swimming and performed in the following manner: the swimmer executes a tumble turn without touching the wall with the hands, starting with movement of the body around a nearly horizontal transverse axis, followed by rotation around the longitudinal axis of the body before, during and after the push off phase (79). The force-time characteristics of the leg extensor muscles in the push off phase is independent of the type of turn employed by the swimmer (62). Given the similarity of the push off techniques it follows that similar dry-land training exercises can be prescribed to improve force generation characteristics for either a touch or a tumble turn.

Swimmers who exhibit higher peak forces generally exhibit faster turn time times (12), reduced wall contact time (16, 96) and greater mean impulse (96) during tumble turns than slower swimmers across an age range of 13 to 24 y inclusive of both genders (59, 60). The ability to generate higher propulsive forces during the push off phase of a turn can improve the velocity off the wall and yield a faster total turn time performance (59). A reduction in turn time correlates highly (r=0.86) with 50m swim performance times (13). Thus, if a swimmer can decrease their turn time they should be able to improve their chances of competitive success.

Relevant studies have only observed swim turn performance with younger aged swimmers, were limited to the knee extension component of the movement,(72) and did not utilize elite level swimmers, nor considered the strength levels of the swimmer (9). Only a small number of publications have reported lower body impulse characteristics in swimming turns (3).

The aim of this study was to quantify the magnitude of differences between dry-land leg force characteristics and swimming tumble turn leg force variables between elite and sub-elite swimmers to prioritize performance parameters for training at an earlier development stage.

Methods

Experimental Approach to the Problem

We employed a cross-sectional design to quantify the differences between dry-land and swim turn leg extensor force-time curve characteristics between sub-elite and elite level swimmers. All data were obtained on the same day for both tests. The swim turn proprietary force plate testing was conducted first, one hour post breakfast, at 8am within a one hour testing session followed by a one hour recovery period before the dry-land testing was undertaken at 10am. All swimmers were tested as part of their camp program and did not participate in any swimming or strength training prior to the two tests conducted on the second day of a five-day camp program.

All subjects were familiar with both dry-land and turn testing protocols via their normal training and testing routines and accordingly a familiarization session was not undertaken. During the data collection sessions participants undertook a standardized warm-up procedure prior to testing. These procedures are outlined below.

Subjects

A total of forty-three swimmers (ranging from 16 to 29 years of age and consisting of 19 females and 24 males) were recruited. All swimmers were part of a national squad of swimmers selected by Swimming Australia and were tested in the early phase of their off season preparation within their yearly plan. The first group was divided into male and female swimmers (n=21, 10 females, 17.1 ± 0.6 y and 11 males, 17.4 ± 0.6 y; mean ± SD) as members of Swimming Australia's Talent Identification (under 18) Squad during a camp conducted at the Australian Institute of Sport (AIS). The experience level of this group of swimmers was less than two years of structured dry-land training and four years of pool training.

The second group comprised male and female elite-level swimmers (n=22, 7 females, 21.6 ± 2.5 y and 15 males, age 23.2 ± 2.3 y; mean ± SD) from Swimming Australia's National Senior Team. The experience level of these groups of swimmers was more than four years of structured pool and dry-land training (see Table 1).

Table 1. Demographic characteristics of elite (male & female) and sub-elite (male & female) swimmers undertaking pool and dry-land testing (mean ± SD)

	Sub-elite		Elite		Standardized difference (qualitative descriptor)	
	Male	Female	Male	Female	Male	Female
Age (y)	17.4 ± 0.5	17.1 ± 0.6	23.2 ± 2.3	21.6 ± 2.5	9.13 very large	5.84 very large
Mass (kg)	74.5 ± 9.8	60.3 ± 5.3	85.2 ± 8.4	67.0 ± 7.2	0.96 moderate	1.07 moderate
Height (cm)	178.9 ± 5.3	170.3 ± 5.3	184.3 ± 9.2	174.2 ± 5,7	1.15 moderate	0.67 moderate
Experience (y)	2.0 ± 0.6	0.5 ± 0.3	5.3 ± 1.5	4.5 ± 1.0	2.96 very large	4.5 very large

This investigation was conducted in accordance with the Declaration of Helsinki and approved by the Human Research Ethics Committee of the AIS and Edith Cowan University. All swimmers provided informed written (parental if under eighteen with participant assent) consent via their Swimming Australia Team Agreement or AIS Scholarship Agreement and informed of the procedures, benefits and associated risks.

Swimming Tumble Turn Testing

Prior to conducting the swimming tumble turn test, all swimmers completed a pool-based warm-up based on their pre-race routine. This warm-up included some sprint, dive and turn drills to ensure the swimmer was ready to perform all of their turns at maximal effort. Each swimmer then performed three maximal effort tumble turns, with a three-min rest period between each turn. The swimmer swam from 20 m out towards the wall at full speed, undertook the tumble turn and swam at maximal effort back out to the 20-m mark. This distance allowed for capture of the full 15 m into the wall and back out to the 15-m mark as the overall turn time. Kinematic and kinetic turn data were obtained using a proprietary force plate system (‘Wetplate’) instrumented and mounted within the pool wall. This system used a wall-mounted Kistler force platform (Z20314, Winterthur, Switzerland) sampling at 500 Hz. All force characteristics of impulse, force and relative peak power were filtered using a low pass Butterworth digital filter with a cut off frequency of 10 Hz. Test retest reliability for Wetplate was undertaken with a sub group of national squad swimmers yielding a coefficient of variation (CV) of 2.4 – 4.7% across the four characteristics measured.

Dry-land Testing

Swimmers undertook a standardized five min warm-up consisting of light aerobic activity performed on a stationary bicycle maintaining a cadence of 80 rpm, a predetermined series of dynamic joint range of motion, and static stretches for the quadriceps and hamstring muscle groups. This was followed by two sets of five repetitions of box jumps, and two sets of five repetitions of the power clean performed with an unloaded barbell (20 kg) to prepare the athlete for the subsequent jump testing.

After completion of the standardized warm-up, all participants performed three unloaded and three loaded (20 kg females and 30 kg males) maximal effort SJ’s, with a two-minute rest period between each jump while standing on a uni-axial force plate (400 Series Performance Force Plate, Fitness Technology, Australia) interfaced with commercially available computer software (Ballistic Measurement System, Innervations, Australia). Squat or “concentric-only” jumps were used as they more closely mimic the predominantly concentric muscle actions of the swim turn. All force data were collected at 200 Hz and filtered using a low pass Butterworth digital filter with a cut off frequency of 50 Hz. All force-time curve variables collected during the jump trials (loaded and unloaded) were then analyzed for peak force, peak velocity, peak power, impulse and peak power per kg of body mass. Each swimmer was instructed to lower their body to the correct start position of the SJ and hold for a count of three seconds before performing the jump. The jump force trace was checked to ensure there was no countermovement prior to the concentric action. A test retest reliability for barbell-loaded squat jump characteristics in our laboratory has been established as a 2.2% CV(90).

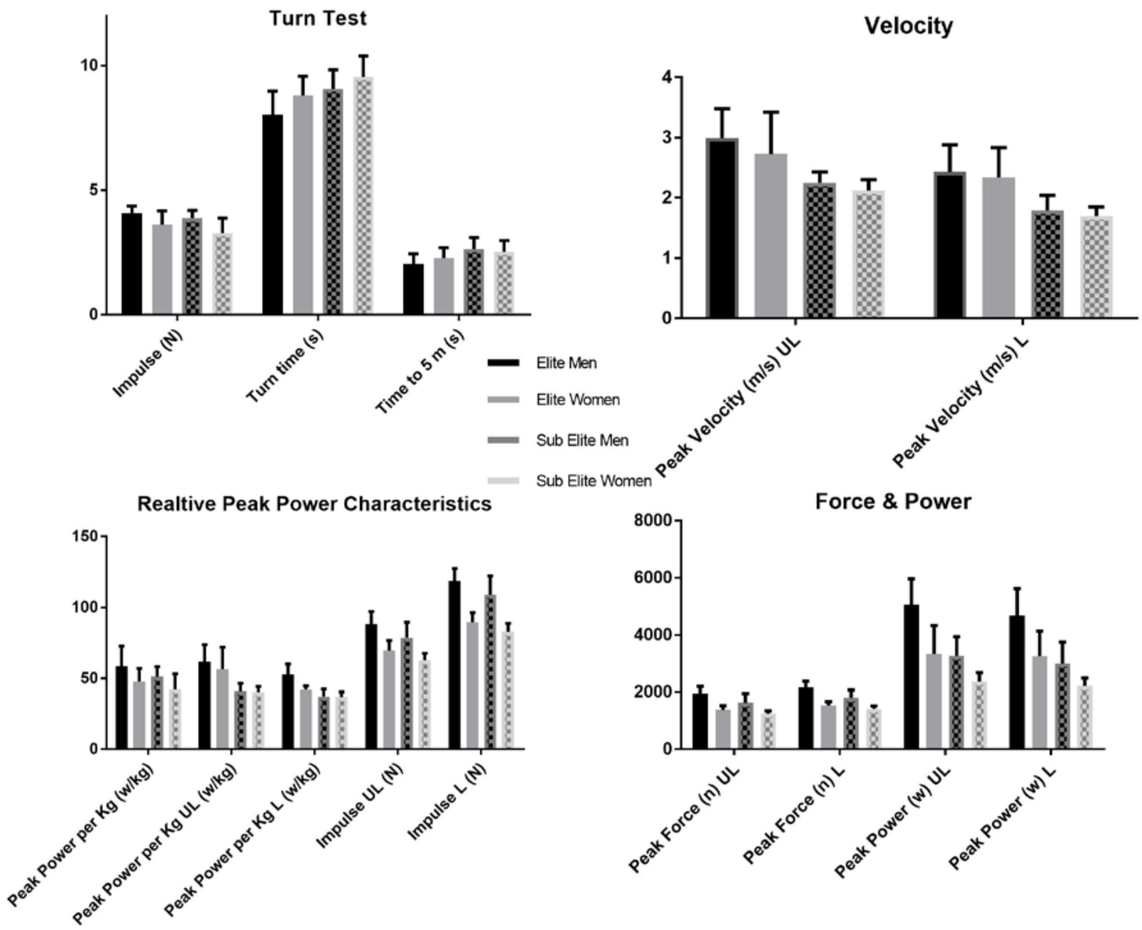
Statistical Analysis

Descriptive data is reported as mean and standard deviation (SD). Inferences on differences in strength/power characteristics between elite and sub-elite swimmers, and by gender, were made using a student's t-test for independent samples. Precision of estimation was indicated with 90% confidence limits. Effect sizes were reported in standardized (Cohen d) units as the difference in the mean with 90% confidence limits. Criteria to assess the magnitude of observed changes were: 0.0 to 0.2 trivial; 0.20 to 0.60 small; 0.60 to 1.20 moderate; and > 1.20 large. The effect was deemed unclear when the confidence interval spanned both substantial positive and substantial negative values (± 0.2 x between-subject SD) (48).

Results

Both swim tumble turning and dry-land force-time curve characteristics in the elite male and female groups were markedly superior to the sub-elite male and female groups (Figure 1). The estimated standardized difference ranged from small to very large (Figures 2 & 3, A and B). The largest differences occurred in the peak power and peak velocity characteristics of the SJ test.

Figure 1. Swim tumble turning and dry-land force-time curve characteristics in the elite male and female groups compared to the sub-elite male and female groups



In the swim tumble turn leg extensor force-time curve characteristics (see Figure 2A & Figure 3A) the Elite male and female groups had superior performance compared to the respective Sub-Elite male and female groups on all key parameters. Specifically, the standardized differences ranged from small to large across the male groups, with the biggest difference being large for overall turn time (Elite males 8.03 ± 0.95 sec, Sub-Elite males 9.07 ± 0.77 sec). The standardized differences ranged from small to moderate across the female groups with the biggest difference being moderate for overall turn time (Elite females 8.81 ± 0.77 sec, Sub-Elite females 9.55 ± 0.84 sec).

Figure 2. Comparison of Swimming Tumble Turn (A) and Dry-land (B) strength power characteristics of elite and sub-elite male swimmers. Standardized difference was interpreted as: trivial <0.2, small 0.2-0.6, moderate 0.6-1.2, large 1.2-2.0, very large >2.0. Results presented as mean ± 90% confidence limits. UL = unloaded, L = loaded

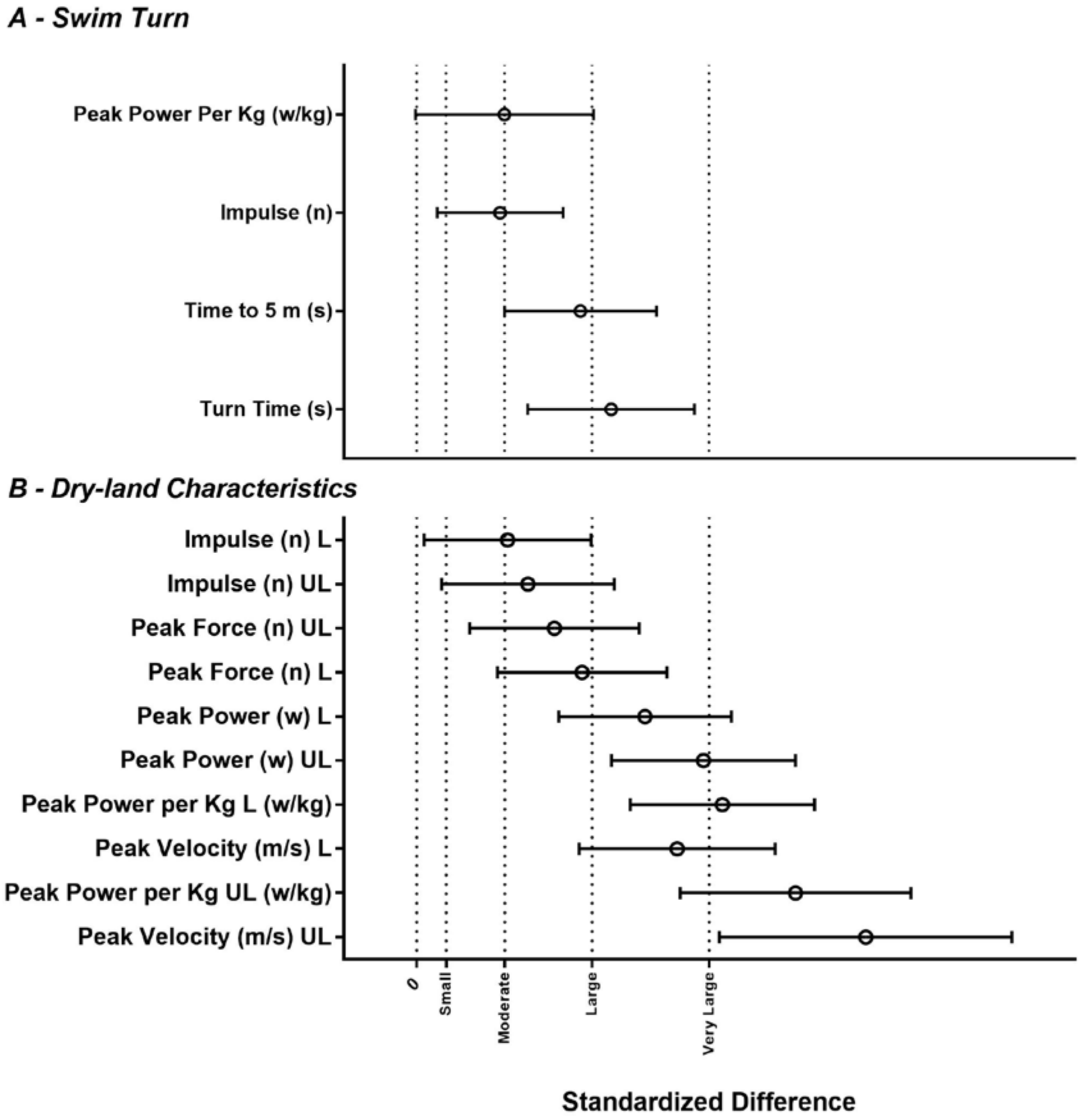
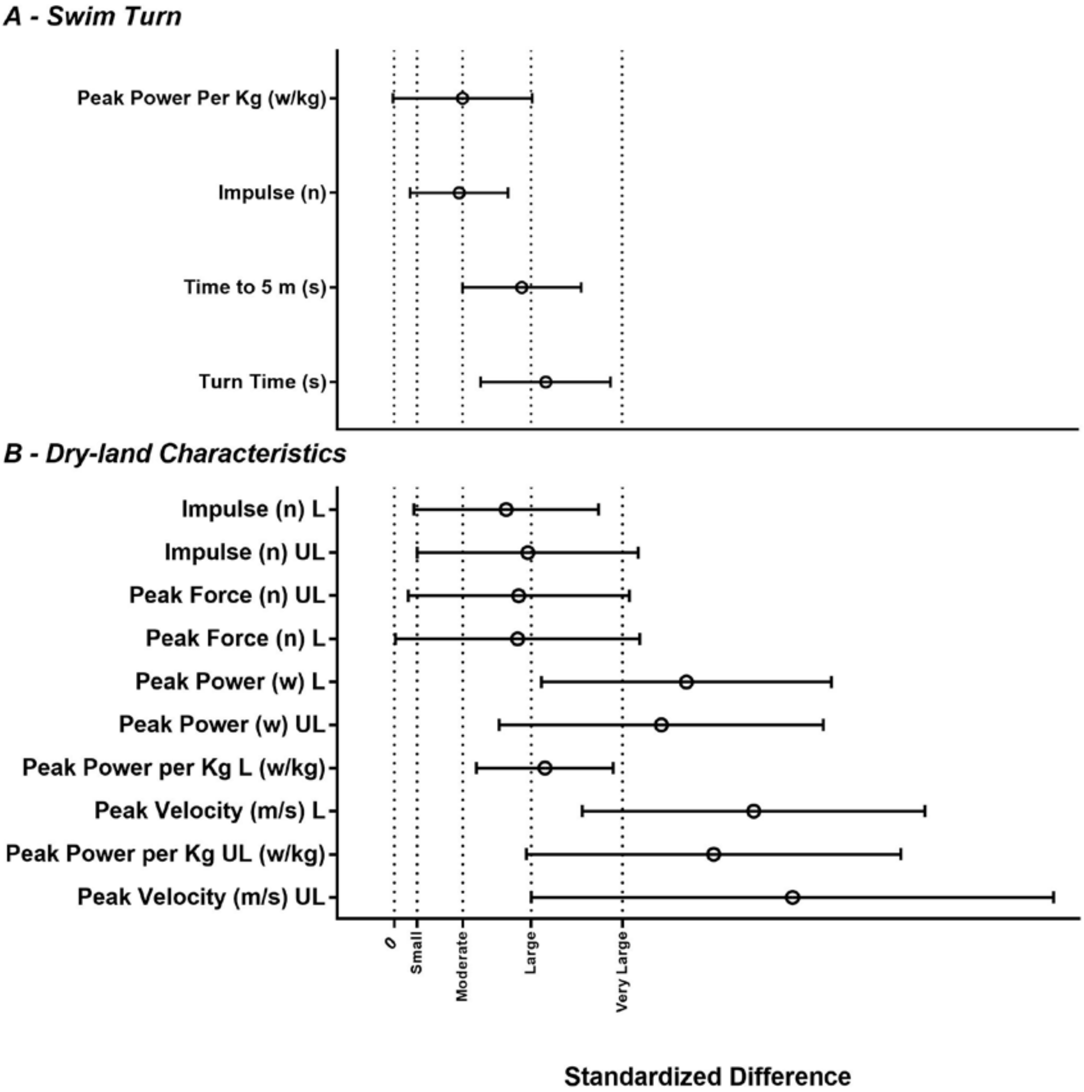


Figure 3. Comparison of Swimming Tumble Turn (A) and Dry-land (B) strength power characteristics of elite and sub-elite female swimmers. Standardized difference was interpreted: trivial <0.2, small 0.2-0.6, moderate 0.6-1.2, large 1.2-2.0, very large >2.0. Results presented as mean ± 90% confidence limits. UL = unloaded, L = loaded



For dry-land leg extensor force-time curve characteristics (see Figures 2 & 3 B) the Elite male and female groups produced superior performance compared to the Sub-Elite male and female groups on all five key parameters in both the loaded and unloaded modalities. The standardized differences between male groups ranged from small to very large and small to very large for the females.

In general, the Elite male swimmers were ~30-50% more powerful than the Sub-Elite males. Very large differences between the male groups were evident in SJ peak power per kg (loaded and unloaded) and SJ peak velocity (loaded and unloaded). The SJ relative peak power (loaded and unloaded) means for the Elite male group were 52.8 ± 7.3 and 61.9 ± 11.7 ($W{\cdot}kg^{-1}$) respectively compared with Sub-Elite male group means of 37.1 ± 5.5 and 40.9 ± 5.6 $W{\cdot}kg^{-1}$, which corresponds to a percentage difference in the means between the two groups of 43 ± 15% and 50 ± 18% (loaded and unloaded; mean ± 90% confidence limits). The SJ peak velocity (loaded and unloaded) means for the Elite male swimmers was 2.4 ± 0.5 and 2.9 ± 0.5 m/s respectively compared with the Sub Elite male group means of 1.8 ± 0.3 and 2.3 ± 0.2 m/s, or differences of 36 ± 16% (loaded) and 32 ± 12% (unloaded).

In general, the Elite female swimmers were ~35-45% more powerful than the Sub-Elite females. Very large differences were evident between the female groups in SJ peak power (loaded and unloaded), SJ peak velocity (loaded and unloaded) and SJ peak power per kg (unloaded). The means of these characteristics for the Elite female group were 3200 ± 870 W and 3400 ± 990 W, 2.3 ± 0.5 m/s and 2.7 ± 0.7 m/s and 57 ± 15 $W{\cdot}kg^{-1}$ respectively compared with the Sub Elite female group means of 2200 ± 280 W and 2400 ± 310 W, 1.7 ± 0.2 s and 2.1 ± 0.2 m/s and 40 ± 4 $W{\cdot}kg^{-1}$. These differences correspond to percentage differences of 44 ± 26% and 38 ± 27% in the SJ peak power loaded and unloaded, 36 ± 20% and 37 ± 112% in the SJ peak velocity loaded and unloaded, and 38 ± 26% in the SJ peak power per kg unloaded.

Discussion

To improve a swimmer's ability to perform a faster turn in training and competition a coach must address the specific characteristics which influence the swim turn performance. This study examined the lower body force and power characteristics that contribute to the push off phase of the tumble turn which is one of the five stages that constitute overall turn time. Force-time curve characteristics were measured in both the pool (swim turn) and gym (gymnasium or dry-land) environments in order to characterize the relationship between dry-land and in-water force production capacities. The primary findings of the present study were that elite male and female swimmers have ~30-50% superior leg extensor strength/power characteristics during jumping and turning tasks when compared to sub-elite male and female swimmers.

We explored force-time characteristics that differentiate between elite and sub-elite swimmers. Differences in force-time curve characteristics between this level of competitors inform the training needed to improve swim tumble turn times of swimmers. Effective program prescription by both swim and strength & conditioning coaches is needed to develop and maintain these characteristics within and between seasons. However, most swimming coaches and their respective strength & conditioning coach are aware that studies have not directly examined the leg extensor force-time characteristics of swimmers during the tumble turn and during dry-land training.

Knowing that the tumble turn is divided up into five stages, and the push off phase relies on the swimmer's ability to rapidly produce force against the wall of the pool during the turning process, it is clear that dry-land leg extensor training can enhance the force generating characteristics of turn time (13, 57, 96). In this study, the greater force and velocity differences exhibited by the Elite male and female groups is the first time that these specific effects have been identified. These data inform training decisions, either dry-land or in pool, of swimmers' activities that will enhance these performance characteristics to approach that of the more elite swimmers.

The Elite male group was superior to the Sub-Elite male group in both the loaded and unloaded SJ relative peak power and peak velocity characteristics. The Elite female group was also superior to the Sub-Elite female group in both the loaded and unloaded SJ peak power and peak velocity characteristics. Large differences between the Elite and Sub-Elite male groups and the Elite and Sub-Elite female groups were observed in turn time and the SJ peak power (loaded and unloaded). The Elite male and female groups superior capacities may be partially explained by the fact that the Elite swimmers had been undertaking dry-land based resistance training for a substantially longer period of time (males 5.3 ± 1.5 y, females 4.5 ±1 y) than the Sub-Elites (males 2.0 ± 0.6 y, females 0.5 ± 0.3 y) providing more time to improve both force application. We expect that the Elite male and female swimmers would have a greater underlying force generating capacity in the leg extensor muscle groups developed by this type of training, as well as faster turn times. The ability of the Elite male and female swimmers to demonstrate this characteristic implies their dry-land training prescription of specific leg extensor strength and power exercises was translated to better turning time.

It is likely that the elite groups of both gender having built a higher strength and power capacity, have a much impulse generation for the push off phase of the swim tumble turn (13, 74). Our data support this assertion as the Elite male and female swimmers expressed higher forces and impulse during their swim turns. While this study has identified greater force and velocity differences by the Elite male and female groups in the dry-land characteristics, further investigation is needed to determine whether improving them directly, regardless of age, improves swim turn performance.

While leg extensor force characteristics can contribute to a faster time in the push off stage, they are only one of many elements that make up overall turn efficiency. Other contributing factors include the technique, dry-land training history, age and height of the swimmer. The likely impact of dry-land training on turning would be small to moderate at best given the longer distance covered in overall turn time than just time to 5 m (31). Factors such as a more efficient streamlined body position and minimizing drag could also explain why the Elite male and female groups demonstrated a faster overall turn time. Given the time to 5 m is one third of the overall turn time, and determined by the force applied to the turn wall, increased strength and power may have a direct influence on increased force application during the turn.

The outcomes of this study provide evidence which inform the dry-land training interventions used by swimmers. There is an opportunity for the swimming coach and/or their associated strength and conditioning coach to improve impulse, relative power and velocity during leg extension of the swimmer. Several studies have examined the effect of enhancing a swimmer's power output on their overall swimming performance (3, 40, 62, 95) but most have only measured upper body performance characteristics (88, 89). More randomized controlled studies with dry-land strength and power training of the leg extensors are needed to determine whether improvements in dry-land force, impulse and power generation are directly transferable to swim tumble turn performance.

Conclusion

Force and power qualities were superior in elite male and female swimmers. The likely explanation for the superior qualities is a longer background in dry-land training as a function of specific training undertaken during their senior careers. The leg extensor characteristics with the larger standardized differences were all dry-land based rather than in the pool. Understanding these differences reinforces the need to enhance the younger swimmer's ability to tumble turn faster by prescribing specific dry-land lower body training. Further study into the benefits of improving these characteristics at either an earlier age, or more extensively, and their effect on decreasing overall turn time is warranted.

Practical Applications

Given the predominance of aerobic training that swimmers undertake on a weekly basis, sub-elite male and female swimmers need leg extensor strength training in their later adolescent years. This training should enable specific strength and power characteristics to be developed more quickly during the transition years from junior to senior swimming. There should be emphasis on concentric-only mode training specific to the types of contractions performed during swimming including leg extension during the tumble turn. Well-developed strength and power should enable swimmers to focus on other training modalities later in their careers. Traditionally in swimming, while the swimmer often undertakes dry-land training from an early developmental stage and age, much of the exercise prescription addresses the upper body and trunk with limited intensive work on the lower limbs. Dry-land training activities should incorporate exercises that target the leg extensor muscle groups with both strength and velocity exercises such as squats, jump squats, lunges and split squats.

Acknowledgments:

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Declaration for Thesis Chapter 4: Comparison of ballistic and strength training on swimming turn and dry-land leg extensor characteristics in elite swimmers

Declaration by candidate

In the case of Chapter 4 the nature and extent of my contribution to the work was the following:

Nature of contribution	Extent of Contribution (%)
Julian V. Jones	70%

The following co-authors contributed to the work:

Name	Nature of Contribution	Extent of contribution (%)
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Chapter 4: Comparison of ballistic and strength training on swimming turn and dry-land leg extensor characteristics in elite swimmers

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Abstract:

Swimmers undertake dry-land resistance training as part of their overall training regime in order to increase lower body force output, impulse and swim turn performance. We investigated whether short-term ballistic training or maximal strength training is more effective in enhancing leg extensor force characteristics during the swim turn. Twelve elite swimmers (10 males and 2 females 19.4 ± 1.0 y) were assigned to either strength (n=6) or ballistic leg extensor (n=6) training based on their coaching group for a six-week period. All testing was conducted during the final training cycle towards the World Championships selection trials. Swimmers undertook dry-land testing of a squat jump (SJ) on a portable force platform with bodyweight only and an additional 30 kg load for males and 20 kg load for females. On the same day, all swimmers performed a turn analysis using a fixed force platform within the pool wall. There were no substantial differences between the strength and ballistic groups after the six-week intervention. Only SJ peak velocity (loaded) showed a moderately large standardised difference (-0.71, ±0.42 m/s) after six weeks in the strength-trained group. Relative peak power (4.0 ± 2.1 W/kg), SJ peak force (loaded and unloaded) (195.0 ±122.8 N, 155.0 ±152.3 N) and SJ impulse (unloaded) (2.9 ± 2.1 N) all showed small and clear improvements with ballistic training over the six-week intervention. Both strength and ballistic dry-land training can improve aspects of the push off stage of the swim turn providing programming options for swimming and strength and conditioning coaches.

Key Words: Swimming, Force, Power, Resistance Training, Ballistic Training

Introduction

In high performance swimming, athletes dedicate many hours of training to attain small increments of improvement or marginal gains in overall performance. To stay in contention for an Olympic medal, a swimmer must improve his or her performance by ~1% within a competition (heats to finals) and by ~1% within the year leading up to the Olympics.(85) To achieve these small increments of improvement, swimmers undertake both pool-based and dry-land training modalities to improve all aspects of their race performance.(6) Swimming race performance can be divided into four key phases comprising the start, free swim, turns, and finish.(14, 69) The swimming turn has been further divided into a number of stages by multiple investigators, the most common being the five stage model of: Inward-Turn, Rotation, Push Off, Underwater and Outward-turn.(63) When examining the influence of the turn phase on swim performance the majority of research has focused on the kinematics and kinetics of the different turn styles.(59) Interestingly, almost all of these studies assert that increased application of force and impulse during the push off stage of the turn by the swimmer can reduce total turn time.(100) However, there is a paucity of studies examining the impact of longitudinal strength training interventions on the force-time characteristics of swim turn performance which can be examined collectively to clarify the contribution of the push-off phase to overall turning time and swimming performance.

Swimmers who exhibit faster overall turn times demonstrate significantly higher peak forces,(13) reduced wall contact time (16, 96) and greater mean impulse (96) than slower swimmers. The ability to generate higher propulsive forces during the push off phase of a turn results in a higher final velocity off the wall.(59) A reduction in overall turn time correlates highly (r=-0.90) with 50 m swim times. (13) Thus, if a swimmer can increase their propulsive forces at a quicker rate, the impact of this higher force should promote faster competition performance.

During a normal training year, the swimmer has to contend with a large amount of concurrent training containing both pool and dry-land content which varies in accordance with the overall periodised training plan.(47) Early in the year, pool training typically consists of a large volume of aerobic-based training followed by a greater focus on anaerobic training. Concurrently during this time, dry-land training focuses on developing strength before transitioning to ballistic training later in the season. This approach makes increasing the swimmer's force application capabilities difficult given a well-documented interference of concurrent strength and endurance training.(38)

One of the major differences between the concurrent training modalities applied to swimmers is that the volume of pool training is considerably higher than the dry-land component. Typically, swimmers undertake nine to ten 1.5 to 2 h pool sessions per week and only three 1 - 1.5 h dry-land sessions. Given the large bias towards pool training, gains in both strength and power might be compromised.(102) In particular, Wilson et al.(102) noted that athletes training to increase their rate of force development (RFD) are compromised more by concurrent training than just pure strength training due to the interference effect.

Dry-land training in swimmers has predominantly taken the approach of focusing on the development of both upper and lower body strength. A majority of dry-land studies have examined upper body power assessments in tethered swimming.(39, 56) The application of ballistic training for the lower limb in swimming performance has only been examined with plyometric activities (21) or in swim starts.(101) One method of training these qualities in swimmers is use of ballistic exercises as part of a comprehensive power development program. Maximal strength training involves heavy resistance, low repetitions and consequently slow movement speed with emphasis on increasing the weight lifted. Ballistic training involves maximal effort against the resistance with the goal of maximal movement velocity, power output and high RFD.(18) Improvements in dry-land strength and power training should transfer to a more powerful and efficient swim turn.(59) However, to the authors' knowledge there are no studies that directly examined the effects of dry-land strength and/or ballistic training on force-time and performance characteristics associated with swim turns in elite swimmers. Therefore, the purpose of this study was to determine whether ballistic training results in a greater improvement in the push off stage of turn performance than a traditional maximal strength program.

Methods

Subjects

A total of twelve swimmers were assigned to a Strength Trained (ST) group or a Ballistic Trained (BT) group based on existing coaching squads and then tested in the pool and on dry-land (Table 2). All swimmers were part of the Australian Institute of Sport Swimming Squad with a minimum of two years of strength training experience. The Strength Group contained six swimmers consisting of four males and two females including a multi Olympic medal winner and World Championship Team members. These swimmers undertook their normal dry-land strength training program over the course of the six-week training block. The BT contained six swimmers consisting of all males including an Olympic Medallist and World Championship Team members who completed a modified dry-land training program with a focus on ballistic leg extensor exercises. The swimmers of both groups performed three dry-land training sessions and 10 pool sessions per week. To assess the effect of the intervention, all swimmers were tested prior to and after the 6-week training intervention on both a dry-land squat jump protocol on a force plate and an in-water turn force plate protocol. The in-water protocol included measurement of key leg extensor force, impulse and kinematic characteristics over the 5 m approach to the wall and to the 5 m exit.

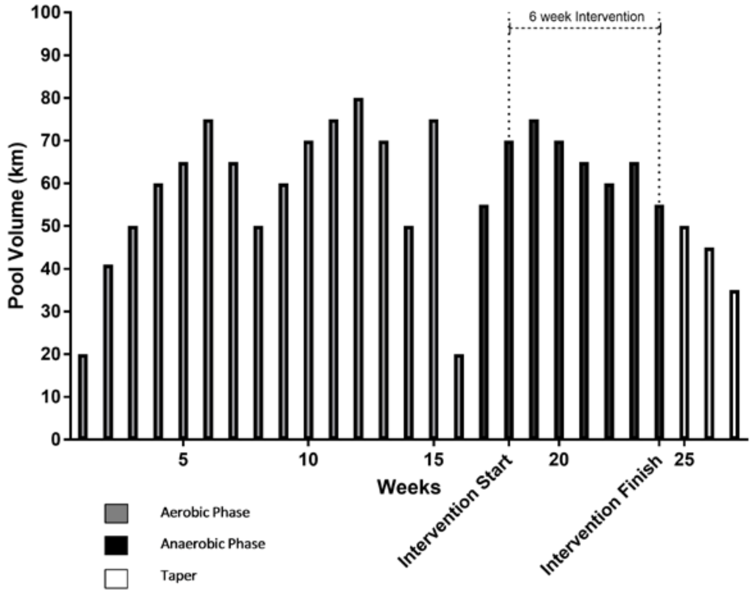
All swimmers were fully familiarised with the testing procedures, as they were part of their usual testing and training protocols. All tests were undertaken in the order of swim turn testing first followed by a minimum of one-hour rest and then the dry-land squat jump test on the same day of the week.

Table 1 – Characteristics of the swimmers in the strength and ballistic training groups.

		Strength trained Mean ± SD	Ballistic trained Mean ± SD
Mass	(kg)	78.9 ± 12.3	77.1 ± 10.2
Height	(m)	1.84 ± 0.09	1.86 ± 0.02
Age	(y)	19.4 ± 1.1	18.9 ± 0.9
Training Experience	(y)	8.3 ± 3.1	8.9 ± 3.5

All swimmers were tested as part of their normal training program in the final preparation period prior to taper (Figure 1) for World Championships selection trials (National Championships). This study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of the Australian Institute of Sport, Bruce Australia and Edith Cowan University, Joondalup, Australia. All swimmers provided informed consent via their AIS Scholarship Agreement and signature of the relevant scholarship papers.

Figure 1 - Swimmers competition preparation plan with identified intervention period



Resistance Training Interventions

The swimmers of the ST training group only performed strength exercises such as squats, dumbbell press and chin ups without the intent of achieving a high velocity. In contrast, the swimmers of the BT training group performed ballistic exercises for the leg extensors with the intent to achieve a high velocity of movement. (Table 2)

Table 2 - Characteristics of the Dry-land Training Program by each Group.

	Exercises	Sets	Repetitions	Load (% RM)	Rest (Min)	Sessions Per Week
Strength Trained	Bench Press, Leg Press, Bench Pull, Shoulder Press, Chin Ups, Squats	4-5	5-8	85-90	3-4	3
Ballistic Trained	Power Cleans, Push Press, Jump Squats, Box Jumps, Medicine Ball Throws	4-5	3-5	80-100	2-3	3

All dry-land training sessions were undertaken 1.5 hours post pool training in the morning. Training sessions were undertaken on Monday, Wednesday and Friday of each week.

Testing Procedures

Swim Turn Testing. Prior to conducting the swimming turn test all swimmers completed a pool-based warm-up based on their pre-race routine. This warm-up included some sprint, dive and turn drills to ensure the swimmer was ready to perform all of their turns at maximal effort. Each swimmer then performed three maximal effort turns, with a three-minute rest period between each turn. The swimmer swam from 20 m out towards the wall at full speed, undertook their preferred stroke turn, touch or tumble, and swam at maximal effort back out to the 20-m mark. This distance allowed for capture of the full 15 m into the wall and back out to the 15-m mark as the full turn time. Kinematic and kinetic turn data were obtained using a proprietary force plate system (‘Wetplate’) instrumented and mounted within the pool wall. This system uses a wall-mounted Kistler force platform (Z20314, Winterthur, Switzerland) sampling at 500 Hz. All kinetic characteristics of impulse, force and relative peak power were filtered using a low pass Butterworth digital filter with a cut off frequency of 10 Hz. Test retest reliability for Wetplate was undertaken with a sub group of national squad swimmers yielding a %CV (coefficient of variation) of 2.4 – 4.7% across the four characteristics measured.

Dry-Land Testing. The squat jump was chosen as there is no preparatory countermovement and thus the stretch shortening cycle contribution is negated. A number of studies have shown that the ‘push off’ phase, which is concentric extension only,(14, 57, 104) makes up the largest percentage of wall contact time.

Squat Jump Protocol. Swimmers undertook a standardized warm-up consisting of five min of light aerobic activity performed on a stationary bicycle maintaining a cadence of 80 rpm, a predetermined series of dynamic joint range of motion, and static stretches for the quadriceps and hamstring muscle groups. This work was followed by two sets of five repetitions of box jumps, and two sets of five repetitions of the power clean performed with an unloaded barbell (20 kg) to prepare the athlete for the subsequent jump testing.

After completion of the standardised warm-up all participants performed three unloaded and three loaded (30 kg for males and 20 kg for females) maximal effort squat jumps, with a two-min rest period between each jump while standing on a uni-axial force plate (400 Series Performance Force Plate, Fitness Technology, Australia) interfaced with commercially available computer software (Ballistic Measurement System, Innervations, Australia). Squat or concentric-only jumps (SJ) were used as they more closely mimic the predominantly concentric muscle actions evident in the swim turn. All force data were collected at 200 Hz and filtered using a low pass Butterworth digital filter with a cut off frequency of 50 Hz. All force-time curves collected during the jump trials (loaded and unloaded) were then analysed for peak force, peak velocity, peak power, impulse and peak power per kg of body mass. Each swimmer was instructed to lower their body to the correct start position of the squat jump and hold for a count of three seconds before performing the jump. Each swimmer’s jump force trace was checked to ensure there was no countermovement prior to the concentric-only action. A test retest reliability for barbell-loaded squat jump characteristics in our laboratory has been established as a 2.2% CV.(90)

Statistical Analyses

Descriptive data are reported as mean and standard deviation (SD). Inferences on differences in the mean change in strength/power characteristics between the ST and BT groups from week 1 to week 6 were made using a Student's t-test for dependent samples. Precision of estimation was indicated with 90% confidence limits. Effect sizes were reported in standardised (Cohen's d) units as the change in the mean with 90% confidence limits. Criteria to assess the magnitude of observed changes were: 0.0 to 0.2 trivial; 0.20 to 0.60 small; 0.60 to 1.20 moderate; and > 1.20 large. An effect was deemed unclear if its confidence interval spanned both substantial positive and substantial negative values (± 0.20 x between-subject SD).(48) A power analysis was undertaken to ascertain if the intervention had enough subjects to confidently determine a significant difference.(48) A sample size of 6 was deemed sufficient to identify a reference change of 4.4% in squat jump peak velocity, assuming a typical error of 1.7%.

Results

The intervention period of six-weeks resulted in the BT showing a substantial within-group improvement in the in-pool test characteristic of Peak Power per kg (Table 3). The BT also showed substantial within-group improvements in the dry-land test characteristics of peak force loaded and unloaded. The remaining twelve characteristics measured from both pool and dry-land tests showed no substantial within-group changes over the six weeks. There was however a large difference at baseline between the BT and ST in relative squat strength; BT had 50% higher (standardised difference 1.79 ± 0.98; mean ± 90% confidence limits) relative squat strength. No substantial changes within or between groups occurred in relative squat strength over the six-week intervention.

Table 3. Comparison of a six weeks of ballistic training compared with strength training in swimming turn and dry-land leg extensor characteristics. There was a substantial improvement in peak power per kg in both groups over the six weeks. Standardized Difference indicates the mean (standardized) difference between the groups in the change in mean value from week 1 to week 6. ES = Effect Statistic

	Strength Trained			Ballistic Trained			Standardized Difference
	Week 1 Mean ± SD	Week 6 Mean ± SD	Change Mean, ±90% CL	Week 1 Mean ± SD	Week 6 Mean ± SD	Change Mean, ±90% CL	Between Groups ES, ±90% CL
Swim Turn Characteristics - Wetplate							
Impulse (n)	3.3 ± 1.0	4.0 ± 0.3	0.7 ±1.1	4 ± 0.3	4.2 ± 0.3	0.04, ± 0.4	0.12, ±0.40
Turn Time (s)	8.1 ± 0.8	8.0 ± 0.8	-0.1 ±0.4	8.5 ± 1.0	8.4 ± 0.9	0.0, ± 0.4	0.15, ±0.5
Time to 5 m (s)	2.2 ± 0.6	2.3 ± 0.6	0.1 ±0.4	2.7 ± 0.7	2.5 ± 0.5	-0.19, ± 0.4	-0.20, ±0.6
Peak Power per Kg (W/Kg)	49.7 ± 19.2	52.3 ± 18.3	2.6 ±9.9	62.1 ± 6.7	66.1 ± 5.2	4.0, ± 2.1*	0.15, ±0.49
Dry-Land Characteristics – Squat Jump							
Relative Squat Strength (Kg/Kg	0.82 ± 0.20	0.8 ± 0.17	0.0, ±0.06	1.2 ± 0.2	1.2 ± 0.2	0.0, ±0.0	0.13, ±0.27^
Peak Power per Kg L (W/Kg)	44.9 ± 8.4	44.7 ± 8.6	-0.2, ±6.1	67.1 ± 9.6	61.1 ± 7.8	-6.0, ±6.7	0.09, ±0.67
Peak Power per Kg UL (W/Kg)	47.1 ± 19.4	48.5 ± 10.2	1.4, ±10.5	62.7 ± 8.6	68.2 ± 8.1	5.5, ±16.7	0.21, ±0.76
Impulse (N) L	107.9 ± 15.3	110.1 ± 12.3	2.1, ±10.2	114 .3 ± 4.2	117.2 ± 7.3	3.0, ±5.0	0.05, ±0.67
Impulse (N) UL	78.4 ± 12.8	83.4 ± 9.0	5.0, ±10.2	85.1 ± 5.2	88.0 ± 6.1	2.9, ±2.1*	-0.08, ±0.68
Peak Force (N) L	1854.3 ± 316.0	1961.9 ± 312.3	107.7, ±163.8	2151.5 ± 154.7	2346.5 ± 221.7	195.0, ±122.8*	0.19, ±0.55
Peak Force (N) UL	1635.5 ± 313.6	1770.7 ± 332.7	135.3, ±211.6	1939.6 ± 175.7	2094.6 ± 212.2	155.0, ±152.3*	0.16, ±0.7
Peak Power (W) L	3620.2 ± 782.4	3652.0 ± 984.3	31.8, ±510.7	5511.6 ± 656.5	5059.0 ± 730.3	-452.6, ± 515.0	-0.23, ±0.73
Peak Power (W) UL	3818.3 ± 1617.3	3930.3 ± 875.2	111.5, ±783.0	5177.7 ± 856.8	5630.1 ± 662.4	452.5, ±1395.3	0.65, ±0.21^^^
Peak Velocity (M/S) L	2.1 ± 0.2	2.1 ± 0.3	-0.01, ±0.3	2.9 ± 0.3	2.5 ± 0.2	-0.4, ±0.2	-0.32, ±1.51
Peak Velocity (M/S) UL	2.5 ± 0.7	2.8 ± 0.6	0.3, ±0.6	3.2 ± 0.6	3.2 ± 0.3	-0.0, ±0.9	0.36, ±0.55^^
Mass (Kg)	80.4 ± 7.3	80.9 ± 8.0	0.5, ±1.8	82.4 ± 4.2	82.7 ± 4.5	0.3, ±1.1	-0.04, ±0.26

* Denotes substantial within-group improvement, L = Loaded, UL = Unloaded ^ Trivial difference, ^^ Small difference, ^^^ different

There was only one characteristic with a substantial difference in the mean changes between ST and BT groups in selected strength/power characteristics in either the pool or dry-land testing the SJ peak power UL, a moderate effect. There was a substantially greater increase in SJ Peak Velocity UL within the ST group. Within the three repeat jump protocol the mean ICC was 0.96 for SJ peak velocity UL and 1.00 for SJ peak power UL and 0.99 for SJ peak velocity L and 1.00 for SJ peak power L. The BT showed small improvements in one pool characteristic peak power per kg and three dry-land characteristics: impulse L, peak force L and UL. Only the SJ peak velocity was improved in response to the six-week training period in the ST group. All other characteristics measured in both the BT and ST had unclear effects (Table 3).

Discussion

The primary finding of the study was that there were no demonstrable differences in performance of the push off phase of a swim turn after completion of 6 weeks of training between the BT or ST groups. Each group exhibited one or two substantial within-group changes in either in-pool or dry-land characteristics. The failure to elicit larger improvements, and in a wider range of strength / power characteristics over the six weeks indicates the challenges for physical development late in the competitive swimming season. Possible explanations for the variable level of improvements include the short length of time of the intervention, the effect of concurrent training, the associated optimal recovery time periods and a relatively low level of strength at the start of the training intervention, in particular for the ST group.

The BT group had small improvements in response to the 6-week intervention period in only one pool characteristic (relative power output) and three dry-land characteristics (impulse loaded, peak force loaded and unloaded). Given that at the elite levels of swimming only ~1% change in performance is expected over a competition year(85) relatively small improvements would be expected with a short intervention period. A number of swimming studies have examined concurrent training and reported that the time taken to gain a meaningful shift can be substantially longer in the presence of competing physiological demands than training in one modality alone.(26, 73, 97)

Izquierdo-Gabarren et al. (49) reported that 8 weeks of concurrent strength and endurance training with rowers using a moderate number of repetitions (not to failure) yielded greater improvements in strength and muscle power than the group who undertook training to failure.(49) In the present study the subjects also did not train to failure in their dry-land strength or ballistic training and undertook similar volumes of concurrent training. In a study by Baar (8) the authors reported performing strength training immediately after a low-intensity volume session results in a greater stimulus for volume adaptation than the low-intensity volume session alone. Taken together this data provides greater support for the rationale that optimising recovery to limit cumulative fatigue is an important consideration when undertaking concurrent training not to train to failure/depletion in either the strength/ballistic dry-land or pool training sessions. These studies were undertaken with upper body interventions only, but followed a similar time course (6 and 8 weeks respectively) to this study. (9)

The initial strength level of a swimmer could influence the rate of improvement in strength/power characteristics. West et al. (101) reported that elite swimmers should have a strength capability of 1.7 times bodyweight in 1 repetition maximum (RM) relative squat strength to improve swim performance. No swimmers in this study had a high level of strength compared with other well-trained athletes given the modest relative squat strength. No substantial effect on the dry-land force characteristics within or between the groups occurred during this intervention. Resistance training interventions that focus on strength development would potentially result in a larger adaptation. Cormie et al. (20) also reported that weaker strength-trained college athletes with a squat of less than 1.3 times bodyweight in 1 repetition maximum (RM) relative squat strength obtained greater gains in both strength and power when targeting strength development. Given that the BT had a higher relative squat strength to the ST at baseline, the outcome of this intervention is not inconsistent with the outcomes of the Cormie et al study. It appears the swimmers in this study needed a combination of strength and ballistic training to enhance or maintain their strength foundation.

Scheduling of the different types of training to optimise the recovery time, and minimize the interference from competing modalities, is important when prescribing the daily and weekly training regime. (77) The programming of the different types of training during this intervention was scheduled only 1.5 hours apart and the limited time might have compromised the swimmers' ability to elicit larger capacity changes with insufficient recovery. Recently, Murach and Bagley (77) suggest that a minimum of 6 hours of recovery should be allotted between concurrent training methods to minimise the interference effect. Further reductions in the impact of the interference effect are expected if 24 hours can be allotted between training factors. These points indicate that the coach should prioritise pool, dry-land and recovery training depending on the primary objective(s) of the training phase, It is also possible concurrent training prevented an increase in muscle mass (hypertrophy).(8) A minimum of 6 hours is needed between factors to minimise the negative impact of concurrent training on muscle hypertrophy. (77) Without hypertrophy, a key component to increasing overall strength levels, a swimmer's ability to make both strength and power gains would be limited. (1) While it is not desirable for swimmers to gain size, given its adverse effect on drag, increasing the underlying strength enables a greater power output and ultimately performance. This study did not undertake body composition testing over the 6-week intervention period and along with no significant change in body mass, the influence of size warrants further investigation. We acknowledge the outcomes of this investigation represent a composite analysis of male and female subjects – further gender specific work is required to more closely define the effects of strength and power interventions within and between the genders in swimming.

Power could be most affected by concurrent training. Wilson et al. (102) speculated that decrements in power result from either impairment of contraction velocity or rate of force development. This may account for the small changes observed in the BT group over the intervention period. It also might explain why other studies (84) did not find any positive effects from plyometric training on performance in swimmers. The ability of swimmers to respond to ballistic training can be limited given the volume of swim training that they carry out for long periods of time. (76) The prolonged periods of volume of greater than 5 kilometres per day at certain times of the preparation cycle can inhibit a swimmer's capacity to recruit large motor units and fast twitch muscle fibres. (37, 38) Given the current intervention was during the final full training preparation phase, the expectation was that the mix of training activities would promote shifts in recruitment of larger motor units. Unfortunately, the final phase of training could not be extended to allow for greater time exposure to the intervention given the upcoming competition.

Conclusion

There was little difference between strength and ballistic leg extensor training on swim turn performance in elite swimmers preparing for major competition. Future studies should consider the amount of concurrent training undertaken if the priority is to enhance strength and power qualities. Optimal placement of the strength and power training cycles should be made in context of the overall yearly training plan as there are limitations to achieving strength and power gains when the swimmers are undertaking concurrent high volume and/or intensity pool-based training. Swimmers need a base level of strength prior to implementing ballistic exercise for best effect. Longer interventions with single modality trained athletes might promote larger improvements in strength/power and swim turn performance.

Practical Applications

As a strength & conditioning coach, it has to be accepted that a swimmer will undertake concurrent training the majority of training year. To enable the swimmer to make significant gains in their ballistic leg extensor characteristics a substantial proportion of time (perhaps longer than six weeks later in the season) is needed to enhance these characteristics without the interference of a high pool training volume. It appears that >1.5 hours of recovery should be allocated between gym and pool training and up to 6 hours would be ideal. The swim coach must collaborate with the strength & conditioning coach to optimise a swimmer's adaptation to both the pool and dry-land training programs.

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Chapter 5: Discussion

Overall turn time in competitive swimming is closely linked with leg extensor force-time characteristics and faster race performance. The current research identified elite swimmers to have superior results in peak velocity, peak force and time to 5m compared to sub-elite swimmers during in-pool and dry-land testing. Two differing training interventions were implemented to ascertain the leg extensor force-time characteristics resulting in the greater performance improvement. The interventions consisted of one group undertaking a normal dry-land strength training protocol; the other undertaking a ballistic exercise training protocol. Neither training protocol showed substantial and clear differences between the groups, however a number of small and clear effects accompanying the ballistic training protocol were realised. Identification of the leg extensor force-time characteristics of greatest importance to elite swimmers, and implementing of the optimal dry-land training protocol, should be considered by the swim coach and support staff in the planning and implementation of the S&C program to achieve a greater performance outcome in the push off phase of the swim tumble turn.

To the author's knowledge this is the first study to examine and quantify which leg extensor force-time characteristics are higher in elite compared with sub-elite swimmers from four in-pool and ten dry-land testing measures. Elite swimmers demonstrated superior leg extensor force-time curve characteristics, but the greatest differences in dry-land characteristics of squat jump peak velocity and squat jump peak power. Identifying these characteristics above other measures enables both the swim coach, and the strength and conditioning coach, to prioritise training prescriptions for these characteristics at certain points in the yearly training plan so as to attain elite level capacities as soon as possible in the swimmer's development.

Differences between elite and sub-elite swimmers in their tumble turn leg extensor force-time characteristics

An assumption is made in high performance sport that the chronologically older athlete with the longer training history will automatically have greater performance capacities in the characteristics of the sport that they undertake. In competitive pool swimming this is especially true as swimmers often start competitive races and training at a young age. Elite swimmers are expected to have greater capacities in many of the in-pool training characteristics given the years of training most swimmers have undertaken prior to starting any formalised dry-land training. Thus, it could be assumed that the greatest gains to be made would be in the performance capacities that the dry-land training can best enhance. Certain capacities and characteristics are a product of the length of time they are trained along with the swimmer's predisposition to a greater ability in certain characteristics compared to others. Determining which force-time characteristics need higher capacities than others in the tumble turn phase of the swimming race is critical for both the swim coach and their S&C coach to prioritise training time.

As the push off phase relies on the swimmer's ability to rapidly produce force against the pool wall during the turning process, it is clear that dry-land leg extensor training may translate into an enhancement of the force generating characteristics of turn (13, 57, 96). Understanding which characteristics have a greater contribution or would benefit overall turn time if enhanced through training makes the compilation of both pool and dry-land training an important element in the coaching of swimmers.

Elite male and female swimmers have ~30-50% superior leg extensor strength/power characteristics during jumping and turning tasks than sub-elite male and female swimmers is a primary finding of this study. Given swimmers start pool training at a young age, twelve or thirteen, but don't start structured dry-land training until they are at least sixteen, it appears that the elite male and female swimmers superior capacities may be partially explained by the fact that the they have been undertaking dry-land based resistance training for a substantially longer period of time (males 5.3 ± 1.5 y, females 4.5 ±1 y) than sub-elite swimmers (males 2.0 ± 0.6 y, females 0.5 ± 0.3 y). This rationale would also provide some insight as to why the elite male and female groups had greater force generating capacities on all the leg extensor force-time characteristics measured.

While a greater force application by the swimmer can contribute to only one of the five stages of tumble turn performance (57), it is only one of the many elements that make up overall tumble turn performance (59). Given force application to the wall is only a small contribution to all of the tumble turn stages the likely impact of dry-land training would be small to moderate at best given the longer distance covered in overall turn time, as it is calculated in the majority of the literature (59), than just time to 5m (31). The turn technique of the swimmer (74), especially knee angle at push off and the ability to apply force quickly (83) and total impulse have been identified as key contributors. Certain variables such as age and even the height of the swimmer also have an impact on their ability to tumble turn efficiently (97).

The above factors along with a more efficient streamlined body position and minimizing drag could also explain why the elite male and female swimmers demonstrated a faster overall turn time, but more importantly also apply in the start phase of the swimming race (10, 81, 101). When the swim coach and their strength and conditioning coach are determining the amount of leg extensor work the swimmer will undertake and the performance gains needed, both the start and turn phases of the swimming race need to be accounted for.

Leg Extensor Force-Time Characteristics that are most different between elite and sub-elite swimmers

This study identified greater relative and peak power, turn time and peak velocity differences in the Elite male and female swimmers for the dry-land tests compared to the sub-elite swimmers. This is consistent with other studies such as Takahashi (96) but this study presented with a much larger sample group in both the elite and sub-elite groups. Large differences between the elite and sub-elite male groups and the elite and sub-elite female groups were observed in force-time characteristics of overall turn time and the squat jump peak power (loaded and unloaded) and squat jump peak velocity (unloaded). The elite male group was superior to the sub-elite male group in both the loaded and unloaded squat jump relative peak power. These superior characteristics are supported by a number of earlier swim turn studies showing swimmers with a greater push off force had higher velocities out of the turn (57), and those with greater force production had a faster time to 5m and shorter wall contact time (74). These superior characteristics are also consistent with a number of swim start studies. These studies indicate that swimmers with greater leg extensor and peak power capacities yield a faster start (53, 72, 80, 101).

Being able to narrow the attention of the priorities in the multiple variables of programming enables the S&C coach to tailor the dry-land program. Given the time taken to realise improvements in these qualities, the ability to target them earlier in the swimmer’s development pathway will enable gains to be made in starts and turns at an earlier development stage. The targeted areas should involve exercises that incorporate force production capabilities at higher velocity. These exercises should be ballistic in nature such as power cleans and jump squats.

Effects of strength and ballistic dry-land training on leg extensor force-time characteristics

In swimming, there are many types of S&C programs prescribed for swimmers to undertake for gaining a performance shift in the strength and power capacities and characteristics to enable a greater performance outcome. In the first component of this research, it was identified that elite swimmers were superior in all fourteen in-pool and dry-land measures. Understanding this and that some characteristics exhibited a greater difference than others, enables the overall yearly training plan to prioritise these characteristics with an appropriate time period that will enable a performance gain. Swimmers at an elite level undertake three dry-land training sessions per week on average and as this makes up 25% of their overall training (78). Knowing what type of dry-land training modality has a greater effect on turn performance would be beneficial to the S&C coach.

There was no substantial difference in performance improvement of the push off phase of a swim tumble turn after completion of 6 weeks of training between the ballistic-trained (BT) and traditional strength-trained (ST) groups. Each group exhibited a number of substantial within-group changes in both in-pool and dry-land characteristics. The failure to elicit larger improvements likely reflects the challenges that face both the swim coach and their S&C coach when trying to periodise across a number of training phases and a prolonged competitive phase or that the prescribed training proved to be rather similar in content given the short nature of the intervention. Possible explanations for the variable level of improvements include the short length of time of the intervention, the effect of concurrent training and inadequate recovery between training sessions and/or days. These difficulties apply in particular for the ST group and the intensity levels of each modality of training and their effects on each other. The ST group's ability to recover between sessions would have been slower due to their lower strength levels across the intervention.

Several studies indicate that the time taken to gain a meaningful shift during concurrent training is substantially longer when competing physiological demands coexist (26, 73, 97). This time is extended when the number of long duration (>20-30 min) pool training sessions (>3 per week) far exceeds the dry-land training volume, to the point of not making any noticeable gains at all in strength and power characteristics (102). A swimmer that is an exponent of the shorter sprint distances during competition should undertake higher intensity pool sessions with less volume as this will result in lower decrements in strength and power (102).

The scheduling of different types of training to optimise recovery time, and minimise interference from competing modalities, is important when compiling and prescribing the daily and weekly training regime (77). Where the objective of the dry-land training is to maintain or improve the swimmer's strength and power levels, then the weekly schedule needs to limit cumulative fatigue. Appropriate placement and content of the different types of training, both within and between sessions, is needed to limit both their interference effect and their effect on immediate and cumulative fatigue.

To minimise cumulative fatigue it is important avoid training to failure/depletion in either the strength/ballistic dry-land or pool training sessions as this will likely reduce a swimmer's ability to fully recover before the beginning of the next training session (9). In a relatively recent study, Murach and Bagley (77) proposed that all concurrent training sessions should have at least 6 hours of recovery between them to minimise any interference effect. Further reductions in the impact of the interference effect are expected if 24 hours can be allotted between training factors. These points indicate that the coach should prioritise pool, dry-land and recovery training depending on the primary objective(s) of the training phase (43).

The initial strength levels of the groups in the intervention study were relatively modest. Both BT (0.8 ± 0.2 $kg \cdot kg^{-1}$) and ST (1.2 ± 0.2 $kg \cdot kg^{-1}$) average relative squat strength were lower than recommendations that elite swimmers should have a strength capability of 1.7 times bodyweight in 1 repetition maximum (RM) relative squat strength to optimise swim performance (101). This low level of strength to start with presents a challenge to elicit strength gains as a key component to increasing overall strength levels is hypertrophy. Given the swimmer's weekly training schedule is that of a concurrent training environment that inhibits hypertrophy (74), the ability of the swimmer to make both strength and power gains would be limited (1).

A swimmer's ability to produce power is dependent on a number of components, with strength being one of them. In weaker individuals, considerable power gains could be more difficult to achieve, as they need a minimum maximal strength capacity to positively affect the power equation. This implies that a performance shift in this capacity would have been expected from the BT group as they initially demonstrated a higher relative squat strength than the ST group (20). Indeed the BT group exhibited small changes consistent with the findings of Cormie et al. (20) that ballistic power training with 0%-30% 1RM resulted in improvements in velocity and power through out a range of loading conditions for the weaker athletes (20). An alternative approach could be that decrements in power result from either impairment of contraction velocity or rate of force development (102). Any further gains in power may have been inhibited the BT group undertaking pool training volumes of greater than 5 km per day reducing the swimmer's ability to recruit large motor units and fast twitch muscle fibres (37, 38). This sequence might also explain why other studies (21, 84) did not find any positive effects from plyometric training on performance in swimmers.

During the intervention period, the three dry-land sessions per week the swimmer undertook were scheduled within 1.5 to 2 hours of the morning high intensity pool session. On these days another pool session in the afternoon was also scheduled. The accumulation of fatigue by scheduling training sessions close to each other has an interference effect on the swimmer's ability to make strength gains. To limit the effect of the high intensity pool session fatigue on the dry-land session at least 3 hours between the finish of the high intensity pool session to the start of the dry-land session is suggested (8).

Improving the endurance response to low intensity in-pool training sessions and providing a strong strength stimulus requires performing strength training immediately after low intensity, non-depleting, pool sessions. During this intervention swimmers undertook at least 40% (3 out of 8) of their pool training at a low intensity with a volume greater than 2 km, but less than 4 km. These low intensity sessions were scheduled to enhance recovery from the high intensity pool sessions and conducted as either the first session the following day or as the second session of the same day in the schedule. This poses the question of reorganising the weekly schedule to enhance the effects of low intensity endurance pool sessions by placing them before the dry-land strength sessions, and scheduling high intensity endurance pool sessions at least three hours before dry-land strength sessions.

A few studies report that in sprint events, swimmers need not undertake the amount of pool sessions that are often scheduled on a weekly basis (25, 26). Costill et al. (25) states that sprint swimmers should confine their pool training to one session of 3 to 5 km each day. If this was implemented in contemporary swim coaching programs then the ability to schedule dry-land sessions with the appropriate time periods of recovery between both pool and other dry-land sessions would be greatly increased. A further study by Mujika et al. (75) recommended that training intensity rather than training volume or frequency, was the key factor in producing a training effect in sprint swimmers adding further support to reducing in-pool training volume and potentially facilitating increased dry-land training.

The placement of sessions, the time between them, and the overall volume of sessions within the weekly schedule impact on swimmers' ability to recover. This is important to enable the acute interference effects of concurrent training to be minimised (55). Residual fatigue from the higher number and volume of in-pool training sessions compromises a swimmer's ability to develop tension during subsequent strength training sessions (70). The overall weekly and monthly training plan needs to be structured to minimise the residual fatigue effect as well as prioritise the modality of training for appropriate periods of time to enhance performance gains within the concurrent training environment.

Conclusion

As competitive pool swimming attracts more and more countries to participate and specialise in particular strokes and events, so the depth of research into performance gains continues to grow. Elite swimmers, both male and female, are superior to sub-elite swimmers in their leg extensor force-time characteristics during the tumble turn and in their dry-land exercises, primarily in relative peak power and peak velocity. When training these characteristics, swimmers and their coaches should determine whether the primary objective of either the pool or dry-land training sessions has precedence. The weekly scheduling of concurrent training should take into account the intensity of the pool sessions and their time proximity to the dry-land sessions to limit interference and maximise recovery. Coaches who expect to elicit a performance improvement in a swimmer's leg extensor force-time characteristics should ensure underlying strength levels are sufficient to enable dry-land training modalities to elicit the maximum positive adaptation.

Chapter 6: Research Outcomes

Elite swimmers have superior leg extensor force-time characteristics than sub-elite swimmers during the turn phase of the competitive pool race. This research also demonstrated that dry-land strength training did not elicit greater performance gains than ballistic dry-land training in terms of enhancing leg extensor force-time characteristics over a six-week intervention period. . It is vitally important that both the Swim Coach and the S&C Coach of the swimmer understand which leg extensor force-time characteristics have greater impact on tumble turn performance, and which dry-land training modality elicits an optimal training effect on these characteristics. This knowledge will enable greater performance gains to be made by the swimmer at an earlier age by prioritising these characteristics over others in the weekly and yearly training programs.

A comparison between elite and sub-elite swimmers on dry-land and tumble turn leg extensor force-time characteristics

Elite swimmers, male and female, were superior on all fourteen-leg extensor force-time characteristics measured both in-pool and on dry-land compared to sub-elite swimmers. Over the fourteen characteristics the standardised difference (effect size) ranged from 0.47 $\pm$0.64; small, relative peak power to 3.49 $\pm$2.29, very large, SJ peak velocity in females and 0.58 $\pm$0.63, small, impulse to 3.07 $\pm$1.00, very large, SJ peak velocity in males. On average both male and female elite swimmers were $\sim 30 - 50\%$ superior across all characteristics compared to sub-elite swimmers.

Elite swimmers have a large number of qualities and characteristics to improve to enable a competitive performance gain to be realised. Allowing both the swim coach and the S&C coach to understand what characteristics need to be trained more extensively than others enables certain periods of time within the training plan to prioritise the know characteristics over others. Being able to target and improve the dry-land characteristics of SJ relative peak power and SJ peak velocity, both loaded and unloaded in sub-elite swimmers earlier in their development will then allow other characteristics to be prioritised in subsequent training plans and programs. Being able to be efficient and effective with the swimmer’s training time at every stage of their development is a priority for all coaches.

Effects of ballistic or strength training on swimming turn and dry-land leg extensor characteristics in elite swimmers

The intervention of splitting elite swimmers into two different training groups for either ballistic or strength based dry-land training, did not yield any substantial changes, but did yield minor changes within or between the groups. The intervention was only six-weeks in duration and there was a large difference at baseline between the BT and ST in relative squat strength; BT had 50% higher (standardised difference 1.79 ± 0.98; mean ± 90% confidence limits) relative squat strength. Given this and the concurrent training nature of a swimmers training with a higher number of pool based sessions than dry-land sessions, only small shifts in a number of the leg extensor force curve characteristics were apparent, predominately in the BT group.

Swimmers undertake a large amount of pool training sessions when compared to dry-land training sessions on a weekly basis. At the elite level on average they undertake eight in pool sessions of approximately ninety minutes and three dry-land sessions of approximately sixty minutes in duration. Given the magnitude of in pool training in comparison to dry-land training, making gains in leg extensor force curve characteristics will likely require longer training periods than 6 weeks. Swimmers would not reach the levels that other athletes of strength and power orientation would be able to achieve for the same anthropometric make up. The placement of certain types of pool training close to dry-land training sessions during the weekly schedule also needs to be taken into account, as well as appropriate recovery periods between different types of training stimulus.

Limitations

Participants in the first study were sourced from national squad members across the senior and under eighteen age group categories. Given the training history of the participants in this study was not captured, it is apparent that these details would give a better understanding of the underlying pattern of differences in leg extensor force-time characteristics.

In the second study the participants were from the Australian Institute of Sport Swim Squad with only a small number of both male and female swimmers. The ability to capture data each week during the intervention was not possible and the timing of performance changes during the intervention may have been missed. Not all participants presented with a relative squat strength level that was commensurate with eliciting large gains in power or force from the ballistic exercises prescribed.

Swimmers across both studies had varying levels of compliance in the dry-land training. Many swimmers will undertake the program prescribed but not necessarily exert the effort needed to attain the intensities required for a performance shift. This shortcoming is usually due to the swimmer being in a fatigued state from the pool training session that is often prescribed close to the subsequent dry-land training session.

Practical Applications

Practical Recommendations for the Swim Coach

In two of the three major phases of the swim race, leg extensor force-time characteristics have an impact on the performance outcome. The phases are the start and the turn. To develop these characteristics the yearly training plan should have priorities for optimising discrete characteristics at certain time periods of the plan. In Australia, elite swimmers usually peak twice a year at major competitions at the domestic and international level. Usually the off-season starts in October after a short break after the main international event for the year. At this time to enable the leg extensor force-time characteristics to gain a large enough shift from the training intervention the following key points should be considered by the swim coach:

- Reducing the amount of pool sessions for the duration of the off-season to allow the adaptations to occur from the dry-land training sessions that increase the leg extensor force-time characteristics.
- Structure the pool training sessions to allow for appropriate recovery periods between all types of training sessions. Appropriate recovery between sessions enables both the dry-land training sessions, to be performed optimally, while reducing the effects of residual fatigue.
- Progressively reintroduce the pool sessions to allow for the swimmer to adjust to the increased pool training volume. This arrangement will enable the swimmer to be less fatigued when undertaking their dry-land sessions.
- Place high intensity swimming sessions at least seventy two hours apart. In this way, neuromuscular fatigue is less likely to impair both dry-land and other pool sessions during the week and allow for as much recovery as possible.

Practical Applications for the Strength and Conditioning Coach

Collaborative work with the swim coach should be a major focus of the strength and conditioning coach to understand and have a positive influence on how the total training plan is compiled. For the swimmer to achieve the performance outcomes needed to be successful at the international level, it is imperative that this working relationship operates with professional respect for each other's expertise. Based on the findings of this thesis the following strategies are recommended:

- The strength and conditioning coach understands the dry-land training is the secondary training priority to the pool training for most of the yearly training plan.
- They must educate the swim coach on the importance of and how to develop the leg extensor force-time characteristics and to prioritise the training of these characteristics for some of the yearly plan.
- Outline that a reduction of pool training will elicit greater performance gains in the leg extensor force-time characteristics. This effect is due to the overall fatigue of the swimmer being reduced.
- A reduction of the pool training sessions is only needed during the off-season training phase of the yearly plan.
- Pool training sessions can be progressively reintroduced without a negative effect on the dry-land training session gains if the overall training volume is managed.

Practical Applications for the Swimmer

Swimmers should be informed on the specific characteristics of their turn performance that need to be addressed first and foremost. Understanding which characteristics play a greater role in elite swimming turn performance while they are sub-elite provides a focus area for the swimmer. Based on the findings of this thesis, the following aspects of education and prioritisation are recommended:

- Understand their training and other commitments during the week need to be planned that optimise the recovery between different sessions to limit one type of training interfering with another.
- Gaining a back squat strength level of at least 1.7 x body weights (101) to enable force production training prescriptions to have the most positive effect on their leg extensor force-time characteristics
- Swimmers would benefit from understanding how the weekly training schedule has been constructed to optimise elements given priority in that particular training phase.

Directions for future research

This thesis has raised the need for more investigation into the effect of increased strength and power on the start and turns phases of the competitive race. Some potential directions for future research include:

- What is the ideal weekly training schedule where both pool-based swimming capacities, and strength and power gains can be optimised?

  Having these two schedules determined will give both the swim coach and strength and conditioning coach the ability to periodise the yearly training plan to elicit appropriate gains in performance parameters with certain blocks of training.
- What are the effects of prioritised blocks of training and competition on the swimmer’s leg extensor force characteristics over a single training year and four year Olympic training cycle?

  A longitudinal study is needed that tracks the effects of prioritised strength training on the leg extensor force-time characteristics over the four-year Olympic training and competition cycles of elite swimmers.
- Do sub-elite age group swimmers improve leg extensor force-time characteristics of peak force and peak velocity when introduced earlier within their dry-land training?
- Do elite swimmers during the start phase of the race prioritise the same leg extensor force-time characteristics as during the turn phase?

  This information would inform the coaching staff on how to efficiently integrate the dry-land training program of the swimmer to cater for both phases of the race.
- Can a swimmer make substantial strength and power gains in an appropriate time period while in a concurrent training environment that has a much larger in-pool training volume than dry-land training volume?

Conclusion

Elite swimmers are superior on all leg extensor force-time characteristics measured and have a greater ability to produce peak force and peak velocity in both in-pool turn and dry-land tests than sub-elite swimmers. Following a six-week training intervention where two dry-land training modalities were implemented with elite swimmers comparing traditional strength training to ballistic training, only the ballistic training group exhibited small positive changes. The failure to yield larger improvements likely reflects a concurrent training environment, a much higher number of in-pool sessions compared to dry-land sessions and the short duration (6 weeks) of the intervention. Swim and S&C coaches should consider how leg extensor force-time characteristics are prioritised, the contraindicated elements are discussed and prioritised, and priority given to the scheduling and timing of both in-pool and dry-land training sessions to minimise residual fatigue and the acute interference effect of concurrent training.

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Appendix

The Appendix is not included in this version of the thesis.